STUDIES ON HORIZONTAL COLLECTOR WELLS

BY

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ARVIND KUMAR SHUKLA

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CERTIFICATE

This is to certify that the thesis entitled "Studies on Horizontal Collector Wells" has been carried out under my supervision and the results embodied in this thesis have not been submitted to any other institute or university for award of any degree.

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Arvind K. Shukla

ARVIND. K. SHUKLA

TABLE OF CONTENTS

LIST OF FIGURES

10(a) to 10( ) Graph showing piezometric head when different discharges are flowing out of well.

11. Collector well under stream bed (Ref. 9)

12. A lateral with assumed linear distribution of discharge

13. Draw down curve under steady state condition.

14. Draw down in the case of a single lat (Ref.9)

15. Location of piezometers in plan

16. Plot showing the interference effect of laterals on discharge.

CHAPTER 1

1.1 INTRODUCTION

With the increase of industries, demand for more and more water is felt. This is creating a great problem. Industrial specification of chemical quality and temperature for process water and for cooling purposes are becoming more rigid (1)* As ground water is usually more constant in quality and temperature, many industries are turning to ground water supplies to satisfy their growing demand. The ever-increasing demand has caused shortage of water supply in many parts of the world. One solution, to some extent, of this is to develop ground water supplies that are dependent upon induced infiltration. The underground reservoirs are filled during period of excess rainfall and can be emptied during periods of drought. In this way the water that otherwise would be wasted into the oceans is saved. The development of water supplies which is dependent on induced in filtration is relatively a new concept.

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* The numerals in parantheses refer to the references given in Appendix - 1.

When a well is pumped, the water level around the well is lowered in the shape of an inverted cone or cone of depression. As the pumping is continued the cone of depression will continue to expand horizontally and vertically until the quantity of water crossing the perimeter of the cone plus the recharge within the area of the cone is equal to the quantity of water being pumped (2,3,4).

Under natural conditions, the water that falls on the earth surface as rain saturates the superficial material and then moves laterally to drain into some surface stream. If, however, a well, infiltration gallery, or water collector located in the alluvial deposits of sand and gravel adjacent to stream is pumped, the cone of depression developed by pumping the well will change the hydraulic gradient and the water will move from the stream towards the well and into the aquifer (5). This process is called recharge or induced infiltration.

The requisite local condition for inducing infiltration includes a surface source of water such as a stream or lake that is hydraulically connected with an aquifer. The aquifer may be a consolidated formation but is usually a deposit of permeable sand and gravel open to stream so that the water may flow in either direction between the surface source and the aquifer.

When a well is pumped the shape of the developed cone of depression in the vicinity is controlled largely by the permeability of the formation, the quantity of water being pumped and the total available head. Under homogeneous conditions the cone of depression is circular in shape and symmetrical around the well. Ground water flows towards the well equally from all directions, if the permeability of the aquifer, the hydraulic gradient and the area through which the water passes are uniform. If, however, a well is placed near a perenial stream that is interconnected hydraulically with the aquifer, the cone of depression will become distorted, and will flow from the stream into aquifer to replace that which has been pumped out. Since sufficient recharge is available from the perenial stream, the cone of depression towards the stream will eventually assume a relatively stable shape. The ultimate quantity of water that can be obtained can be determined in advance by a detailed hydrogeological survey.

The cone of depression developed by all wells is made up of a head loss due to the movement of water through the aquifer to the well plus an additional loss in head required to move the water through the screen and to the pump intake. Thus well loss factor is due to the change from laminar to turbulent flow. In some cases it is half

the total drawdown in vertical wells. It is only a fraction of total head in the case of collector wells. Collector wells are a new device for providing large supplies. In this we can utilize the full available head in aquifer because of the large amount of screen that can be projected, as much as 200 ft or more of lateral lengths. The entrance velocity is low, thereby minimizing sudden changes in pressure and well loss and eliminating encrustation. The yield of individual collector may exceed 20 million gallons/day under favourable conditions. A brief description of horizontal collector well is given below.

1.2 DESCRIPTION OF A HORIZONTAL COLLECTOR WELL

A horizontal collector well consists of the following (6) :

A central caisson, i.e., a sectionally poured in-place reinforced concrete vertical shaft of large diameter, 13 ft or more, is sunk as a caisson to a predetermined depth. The average depth of caisson below ground level is 70 ft, although in some cases the depth is more than 200 ft. The wall thickness for a relatively shallow collector shaft is 18 inches and for a relatively deep one, 24 inches. The bottom of caisson is a heavy

reinforced concrete slab, the thickness and the weight of which have no effect on caisson stability, owing to the interrelations of caisson size and weight.

Approximately 4 ft from the bottom of caisson shaft are one or more tiers of horizontal perforated steel pipes surrounded by a screen and connected to a valved port. The ports are usually no less than $22\frac{1}{2}°$ apart. The collector piping usually has an 8.5/8 inch outer diameter and a 3/8 inch wall thickness made of copper alloy steel. The slots in the pipe cut with a saw, are 3/8 inch wide and $1\frac{1}{4}$ inch long, the perforated area equals about 20% of the total surface area. In the "Ranney" well, slotted pipe is placed directly. Whereas in "Fehlmann" well a blank casing is installed after which a perforated pipe is placed inside and the blank casing removed.

The total length of the collector pipe required depends, as determined in the field test, upon the quantity of water, minimum loss of head, porosity and transmissibility of the formation. The lower the entrance velocity, the better the water quality, the fewer the small particles that enters the collector, and the smaller the chance of encrustation.

After a preliminary survey has confirmed that the aquifer is suitable for development and a pumping test has determined that the yield is adequate, a reinforced concrete caisson is sunk into the ground to the required depth (7). Normally this is done by building a circular section of the caisson, about 10 ft. in height on the surface and digging out the enclosed earth to allow the section to settle into the ground; the operation is repeated until required depth is reached. The bottom of caisson is then plugged with reinforced concrete and when this has set the development of infiltration galleries or the horizontal laterals can start.

From portholes formed at the bottom of caisson wall, laterals are projected horizontally like the spokes of the wheel. These are fabricated from heavy steel pipes perforated with longitudinal slots and may be 8,12, 24 inch in diameter. The number of laterals installed and the length of each is determined by site conditions and the yield requirements. The development and projection of the laterals are the most important phases of the entire operation. Each new section being welded to the one previously installed with straight forward method of thrusting, however the pipes could not be pushed to any great length and

further they would compress the materials of the aquifer making collection of the water more difficult. In the horizontal collector system the fine sand and gravels in the path of the projected pipe are removed by flushing, from 2 to 4 cu ft of fines being removed for every foot of pipe projected. After development each lateral simply serves as a sub drain in a filter surrounded by a material, several ft in dia, of course gravel. Fine slotted laterals surrounded by artificial gravel pack, have been developed for formations which do not contain any natural gravel. A major advantage of the horizontal collector system is that any required area of screen opening can be developed so as to control the entrance velocity of water into the laterals. By keeping the velocity of the water extremely low, sand entry and encrustation can be controlled. Encrustation is caused by the precipitation of calcium carbonate from the water. When water passes through screen at a high velocity there is a lowering of pressure allowing a portion of the CO_2 dissolved in the water to be liberated This causes a change in the bicarbonates, not only on the surface of the screen, but also in the interstices of the surrounding gravel. The design of horizontal collector well is based upon projecting sufficient laterals to keep the velocity through the screen

of the slotted pipe and adjacent aquifer low enough practically to eliminate the pressure drop.

Within the caisson, at each porthole where a lateral is installed, a gate valve is fitted. The opening of these valves converts the lower part of the caisson into a pump well of naturally filtered water, the upper part of the caisson can be used to house the pump, motors and control gear, so that a complete water producing system is contained in one unit, provided that the upper part of the caisson is built well above maximum flood level. A clean uncontaminated water supply is always available despite wide spread flooding and silting. Apart from water abstraction, Ranney system can be used to recharge aquifers without necessitating the construction of large ponds.

1.3 CHEMICAL QUALITY OF WATER

The water used in industries should be of good quality and should be in sufficient quantity. In the collector wells all the organic matter and pathogenic bacteria are removed from water by induced infiltration. Studies show that the major factor in the distruction of organic matter is oxidation. This distruction is sufficiently effective to remove even phenols from water pumped from horizontal collector installation along Ohio river.

Records of chemical quality of water from a collector well of the central fibre products company at Quincy, Illinois (3) over a period of more than two years show the changes in the chemical quality of the original water pumped which was normal ground water containing 945 ppm total hardness, 1010 ppm chlorides, 450 ppm alkalinity and 25 ppm iron. After one year of pumping iron had dropped to 3 ppm and alkalinity from about 290 to 150 ppm.

The temperature of water obtained by induced infiltration will fluctuate in a manner similar to the fluctuation of temperature of the stream source, however the range of fluctuations will be too small and the maximum temperature of induced infiltration water will lag the maximum temperature of the surface stream by as much as 3 months (3). The temperature of Wabash river fluctuates generally between 37°F & 82°F, the temperature of the collector water however ranged between 47°F & 61°F, though collectors were located very close to river.

Rorabaugh (12) gave the data of national carbide company at Louisville, Kentucky, U.S.A. on the temperature of water from collectors. Thermo-couples were installed in atleast 3 lateral screens and records were kept of

temperature of the water from collector, and the water discharged from individual laterals extending towards the river He showed that the aquifer is an effective heat exchange unit and that its effectiveness can be increased if the distance to the effective line of infiltration is increased.

1.4 THE YIELD FROM A COLLECTOR WELL

The yield of a horizontal collector well depends upon :

i) Thickness of water bearing formation

ii) The available draw down

iii) The effective radius of the well

iv) The permeability of the water-bearing formation

v) The distance to the effective line source or effective line of infiltration.

The thickness of the water bearing formation and the available draw down can readily be determined by proper geologic exploratory test drilling in the area of the proposed development. The effective radius of the well can generally be estimated from the type of well construction, and the coefficient of permeability. The distance to the effective line source can best be determined by field pumping tests.

The basic yield equation assumes a constant water surface and a constant temperature. Since all surface sources have considerable seasonal variations in stage and temperature, a seasonal variation in the yield of the well will occur.

Variation in river stage will directly affect the available draw down and in an unconfined aquifer, will also affect the average saturated thickness of the formation. The water produced from a well dependent upon induced infiltration will have a seasonal cyclic temperature variation similar to that of the surface source, but the variation is less in magnitude than that of the surface source and lag the surface source cycle in time. The changes in viscosity caused by temperature fluctuations will cause a direct variation in yield of well, it is therefore necessary to determine temperature curves for both the river and well. The effective distance to the line source will also vary with stage and temperature because it is controlled by vertical permeability or infiltration rate of the surface source. For cities and industries located near rivers, the problem of obtaining a high quality, low temperature water at reasonable cost has become increasingly difficult. In many places in

Europe and the United States, ground water pumped from collector wells has proved to be a successful solution.

Since the development of collector well, some 400 Ranney collectors have been installed in U.S.A., Canada, France, Germany, Switzerland, Austria, Itly, Yugoslavia, etc. The median yield of a single collector is estimated at 6000-7000 g.p.m. However the yield of a radial well can be increased, if required later, by the projection of further laterals.

The yield of a collector well is generally found using Dupuit-Forchheimer well discharge formula with an experimentally suggested equivalent well radius (13). That is, collector well is replaced by a hypothetical vertical well that completely penetrates the aquifer and is equal to that which obtains in the collector well. The suggested value for the equivalent well radius is approximately 75% of the average lateral length in the collector well system. The flow pattern around a collector well is however, extremely complex. The thickness of the aquifer and the length, location and number of laterals are important factors in the determination of yield of, and the draw down distribution around such wells.

Many studies have been done in the past on radial collector wells. The best and most upto date approaches

to the problem are the results of experimental studies of R. Haefeli and J. Zeller (14), G. Nahrgang and F.K. Falcke (15), B. Kordas (16), M. Milo Je vic (17) and the analytical studies of G. Cocchi (18), P. Ja. Palubarinova Kochina (19) and M. Hantush & I.S. Papado pulos (20).

Haefeli and Zeller performed experiments in a scale model of a well showing the radial symmetry, duplicating ground water flow in a homogeneous and isotropic free water table aquifer of limited thickness. The construction of the laterals was such that the head loss along them was negligible. They obtained the following empirical equation

$$Q = \frac{L.m.k.H \left(\sqrt{A - B\frac{h_o}{H}} - 1\right)}{C} \qquad (1)$$

where

L = length of one lateral assuming all laterals to be of equal length.

m = number of laterals.

k = coefficient of permeability

H = static undisturbed ground water table

h_o = depth of water in the well above the base of aquifer under pumping conditions and under a discharge Q

A,B,C = constants

The constants A,B,C are given in table 1-1 below :

TABLE 1-1

VALUES OF CONSTANTS A,B, AND C APPEARING IN EQUATION (1.1)

m	A	B	C
4	4.00	3.00	5.25
8	3.20	2.90	7.31
12	4.068	3.068	10.00
16	3.718	2.718	11.20

All the constants (A,B,C) in equation (1.1) are dimensionless. The dimension and the values of Q depends on units in which H, k and L are expressed.

Nahrgang and Falke also performed hydraulic scale model investigations. The most important objective of their studies was the significance of the flow through infiltration gallerys. Their study was mathematical as well as experimental. They have shown that the relationship

between the headloss along the laterals and the total drawdown has a great effect on the capacity of the well, and on the relationship between the capacity and drawdown.

Kordas performed experimental investigations on an electrodynamic analog model dealing with the capacity of the symmetrical radial collector well in artesian homogeneous and isotropic aquifers and without ground water flow prior to the well operation. He made the assumption that the head loss along laterals may be neglected, an assumption which may be valid in many cases. Kordas summerized the results of experiments conducted by K. Hunerberg (21), H. Stack (22) and M. Milo Jevic in the form of an empirical equation which is

$$\frac{Q}{KL(H-h_o)} = 4.52 \; \frac{n^{175} (t/L)^{.10} \left(\frac{d}{2L}\right)^{.15} \arctan \; (T/L)}{\log_{10} \frac{R_a}{1.93L}} \qquad (2)$$

where

T = aquifer thickness

R_a = radius of action of well

d = diameter of the collector pipe

t = elevation of the lateral above the impervious stratum.

Equation (2) like all empirical formula is valid within certain limits which are given in table 1-2.

TABLE 1-2

LIMITATIONS OF EQUATION (2)

$.161 \leq H/L \leq .465$,	$1.54 \leq \frac{R_a}{L} \leq 4.44$
$.00846 \leq D/L \leq .0244$,	$.00423 \leq /L \leq .0122$
$0.0 \leq \frac{h_o}{L} \leq 1.0$	

Analytical solution given by Cocchi had the same aim as the experimental approach of Kordas. The basic assumption of Cocchi were that the head loss along laterals may be neglected and that the specific yield along laterals may be expressed by an algebraic polynomial of the second order. The calculations are rather tedious.

The analytical solution given by P.Ja Polubarinova Kochina (19) deals with a special case of the problem of a system of horizontal drains in a semi infinite space of ground water. In particular the problem of yield computation for systems similar to that adopted in the project of water lines in Warsaw is discussed. An approximate hydrodynamic solution is given using the familiar method

of + ve and - ve sources of constant intensity distributed along the axis of the drain whose length is denoted by 2c The yield in a simple horizontal drain is given by equation (1.3) below

$$Q = lq = \frac{2\pi k\,(H + Z_o - P_o/\rho g)\,l}{l_n \dfrac{2Z_o}{b} - l_n \dfrac{c + \sqrt{c^2 + 4Z_o^2}}{2c}} \qquad (1.3)$$

where

l = length of drain

Z_o = drain depth below water surface

H = depth of water

l_n = log

If the radius of the drain is r, then the minor half axis b of an equipotential surface can be assumed as being equal to 1.225 r. We can also assume that $l = 2c$.

$$Q = \frac{2\pi k\,(Z_o - h - \dfrac{P_o}{\rho q})\,l}{l_n \dfrac{2c}{b} - l_n \dfrac{c + \sqrt{c^2 + 4Z_o^2}}{2Z_o}} \qquad (1.4)$$

Equation (14) represents the yield of an horizontal drain below the free surface of ground water occupying initially the lower semi infinite space limited by a horizontal plane. The maximum lowering of the free surface caused by the action of the drain is denoted by h.

P_o = pressure in the drain assuming atmospheric press equal to 0

ρ = density of water

g = gravity acceleration

k = coefficient of permeability

The most recent paper on the collector wells is by M. Hantush and I.S. Papadopulos. This paper deals with steady and unsteady flow towards the collector well. Aquifer characteristics can also be found out by carrying out pumping tests from collector wells. Solutions for problem of flow towards steadily discharging, partially penetrating vertical wells have been obtained by treating the well as a line source, the strength of which is ($\dot{Q}$) is uniformaly distributed along the water entry portion of the well. Also it is assumed that aquifer is homogeneous.

If each of a group of N laterals of a collector well is replaced by finite line sink of uniform discharge

along its axis and if the draw down by ith lateral at any point (r, θ, z) is si then total draw down

$$S = \sum_{i=1}^{N} si = \sum_{i=1}^{N} \left(\frac{Q_i}{l_i}\right) f_i \; (r, \theta, Z, t; \theta_i \; Z_i) \qquad (5)$$

where

f_i = function satisfying boundary value problem

Q_i = discharge

l_i, θ_i, Z_i = length, orientation, vertical position

If discharge from each lateral is same then

$$Q = \left(\frac{Q}{N_l}\right) \sum_{i=1}^{N} f_i \; (r, \theta, Z, t; \theta_i, Z_i) \qquad (6)$$

In the equation (6) it is assumed that flux entering in the laterals is uniformly distributed along its water entry face. But it is found that both flux, & head along the face of lateral changes. Draw down distribution in the laterals is in between these two.

The location of maximum draw down on the face of lateral is dependent on geometry of collector well i.e. how many laterals are there in the collector well.

For $r_c = .05\ell$, this point of maximum draw down can be taken at the face of the well if the number of laterals is four. For six or more lateral if $r_c = .1\ell$, the same approximation holds good. r_c = effective radius of caisson. This point is independent of the hydraulic property of the aquifer. If $(r_m, \theta, Z_1 \pm r_w)$ are the coordinate of the point of maximum draw then draw down is

$$S_{1n} \text{ collector} = \frac{Q_1}{I_1} f_1 (r_m, \theta_1, Z_1 \pm r_w, t; \theta_1, Z_1)$$

$$+ \sum_{i=2}^{N} \frac{Q_i}{I_i} f_i (r_m, \theta_1, Z + r_w, t; \theta_i, Z_i) \qquad (17)$$

where r_m is the radial distance to the point of maximum drawdown. For symmetrically located laterals eqn (17) becomes

$$S_c = \Big\{ f_1 (r_m, \theta_1, Z_1 \pm r_w, t; \theta_1 + Z_1)$$

$$+ \sum_{i=2}^{N} f_i (r_m, \theta_1, Z_1 \pm r_w, t; \theta_i, Z_i) \Big\} \qquad (18)$$

M. Milo Jevic (17,23,24) considered the possibility of an analytical solution of the yield of both, a single collector and a group of such wells, located adjacent to

the river bank in an artesian aquifer of constant thickness. The analytical solution was obtained in the form of algebraic equation with the coefficients in the form of convergent single and double infinite series. This solution did not prove convenient for practical use. He therefore chose an electro hydro dynamic anology as his model. The phenomenon which could not be studied was the variations of water head along the drains due to streaming inside them as well as inside the drainage gallery created around the drain. It was assumed that ϕ = constant along the drains.

The electrical measuring device which was used allowed the following measurements to be made.

(1) The overall resistance R in the model by the wheat stone Bridge with a built in oscillator for frequency of 1000 HZ.

(2) The current, I, passing through the model at a given tension, by measuring the tension drop with an electronic volt meter in a resistor connected in line with the model.

(3) The yield distribution along drains. This measurement was done by dividing all model drains in 10 portions , each portion being electrically insulated

from the other and connected to the feeding source through a resistor in which the tension drop was determined by the electronic volt-meter.

Graphs prepared by him can directly be used for practical purposes.

The yield Q of the well is given by the expression

$$\frac{Q}{2\pi k(H-h)\,T} = \frac{1}{A} \qquad (9)$$

where

A = dimension less function of the well geometry, of well spacing and the river bank distance.

Current I passing through model is,

$$\frac{I\rho}{2\pi\ TU} = \frac{1}{B} \qquad (10)$$

where

B = dimensionless function and depends on the factor on which A depends.

On account of the similarity of the model and the prototype we can take A = B

$$\text{then} \qquad \frac{Q}{KT\ (H-h)} = \frac{\rho}{TR} \tag{11}$$

yield as dimensionless quantity is given by $\frac{Q}{KT(H-h)}$ and as a function of

$$\frac{1}{\log Sh \dfrac{2\pi bL/C/L}{Sh\ \pi/c/L}}$$

where

c = distance between collector wells.

T = aquifer thickness

b = distance of well from source

Fig. 1 shows the above relationship for the case of 8 laterals & 12 laterals.

Yield in an infinite array is given by

$$Q = \frac{2\pi K T\ (H-h)}{2.3 \log \dfrac{Sh\ 2\pi\ b/c}{Sh\ \pi r_o/c}} \tag{12}$$

CHAPTER 2

2.1 INTRODUCTION

The radial collector well was developed and became practical in the 1930's and from time to time improvements are being made. In recent years the horizontal drilled well has gained prominence, in cases where it advantageously replaces the conventional vertical well. Many municipalities throughout the world have successfully operated this type of infiltration gallery to obtain part of their water supply. Radial collector wells provide an inexpensive and relatively simple method of obtaining water of high quality for industrial and municipal use.

The initial cost of a collector well exceeds that of a vertical well, however advantages of large yields reduced pumping heads and low maintenance costs are factors to be considered. Yield vary with local conditions the average for a large number of such wells approximated 5000 g.p.m.

A shaft of sufficiently large diameter is sunk down into the water bearing strata and a number of horizontal well pipes are driven out in radial directions. Methods are connected with the names of Ranney and Fehlmann. This

arrangement is necessitated when the circumference of a conventional vertical drilled well would provide too small an entrance area for the required supply. This occurs in fine grained material in unconfined flow and in coarse thin layers under confined conditions.

For proper design and operation accurate depression curve within well area should be known. To investigate all the phenomenon required for proper function and design of well a model is constructed to simulate the characteristics of the actual aquifer, and to see the various effects such as draw down curves for various discharges, effect of different arrangement of laterals on draw down curve for different discharges, etc.

2.2 CONSTRUCTION DETAILS OF THE MODEL

A masonry tank was constructed on a steel plate bottom The outer dimension of the tank were 8'x8'x4'. The bottom steel plate rests over the two pillars on the side and two continuous walls having height of 3.1/2' to provide working place below the tank. On the plate, brick walls of the tank were constructed giving offsets. Angles irons were provided between the walls and the pillars. In the bottom steel plate holes were drilled in concentric

circles. Fig shows the arrangement of the holes in the steel plate. Piezometers were fitted through these holes. These piezometers go to different heights. The piezometers are made of 1/4" ~~outer~~ inner diameter G.I.Pipes with bottom and screwed to the steel plate. Piezometer tips were formed by drilling 20 holes of 1 m.m. diameter in the top one inch of each piezometer. These tips were wrapped with .283 m.m. wire mesh to prevent sand from entering the piezometers.

The piezometers were connected to vertical glass tubes which are mounted on a wooden board. Usually piezometric heads are measured by putting small holes in the bottom plate and connecting these to vertical glass tubes, but this measures ~~total~~ piezometric head at the bottom of the plate only and does not give the correct water surface profile because of the curvilinear flow net. In model experiments which are of small dimension this shift can be neglected, but not in all cases. In the present set-up the piezometric tubes are raised to various heights in order to minimize this effect.

In the center of the plate a drain pipe of 8 inch diameter was placed as shown in Fig. 2. For measuring water level in the drain pipe a hole was made in the pipe

at the base of the pipe and connected to a glass tube on the wooden board. The length of laterals used was 30" having outer diameter 1/2 inch and internal diameter 3/8 inch with 64 holes drilled on the four faces at equal spacing. The diameter of these holes are 11/32 inch. Laterals were also wrapped with wire mesh of 0.283 m.m. gauge to prevent the entry of the sand.

Sand used in the model was coarse one, grain size ranging from 0.3 m.m. to 1 m.m. grain size distribution is shown in Fig. 3.

A cage of 6 ft. diameter was constructed with the help of I.S. angle and mild steel flats and expanded metal frame. Over this a wire mesh of .283 m.m. gauge was wrapped This cage was filled with sand and around the cage water was filled in the tank from an inlet at the bottom An outlet is provided for the over flow of water The cage prepared provides the sand uniform saturation. Supply of water to the inlet is provided by a 2.1/2 inch pipe connected with a motor of 3 H.P. Outlet is 4" below the top of the tank on one of its side.

The drain pipe of 8 inch diameter was connected to a reducer (8" to 3") at the bottom of the plate and a long pipe of 3 inch internal diameter was taken out

from the reducer, and connected to a tank of dimension 30.5" x 29.5" with a regulating valve.

The cage was filled with a sand of uniformity coefficient $\frac{d_{60}}{d_{10}} = 2.9$ and the effective size $D_{10} = .34$ m.m. The coefficient of permeability of the sand was .030 cm./sec.

2.3 SCOPE OF THE WORK

The flow pattern around a collector well is extremely complex. Thickness of aquifer, length, location and number of laterals are important factors in the determination of yield and draw down distribution around such wells.

Following are the parameters which are to be studied with the help of the present set-up.

(a) Number of laterals
(b) Length of laterals
(c) Elevation of laterals
(d) Arrangement of laterals
(e) Relationship of discharge vs. area of the openings in the laterals.
(f) Determination of the equivalent vertical well radius in the case of unsymmetrical pattern of laterals.

Since all surface sources have considerable seasonal variations in stage and temperature, a seasonal variation in the yield of the well will occur. It is important to define stage and temperature conditions for which the yield is being determined.

Variation in river stage will directly affect the available draw down and, in an unconfined aquifer, will also affect the average saturated thickness of the formation. The effects of this variation can be handled simply by comparing the stage conditions existing during the pumping test with those expected for the conditions for which the yield is being computed, and correcting the draw down and thickness accordingly.

(a) Number of laterals - Discharge and draw down in the drain pipe were measured and shape of the draw down curve is obtained by plotting the piezometric heads at different points.

(b) Length of laterals :- With different lengths of laterals, discharge and draw down were measured.

(c) Elevation of laterals :- Laterals were mounted on the drain pipe in three tiers. Six inches apart vertically starting from the base of the drain pipe. Draw downs and discharges were measured for each elevation separately.

(d) Arrangement of laterals :- Draw down, discharge and shape of the draw down curve should depend upon the arrangement of laterals. Firstly the observations were made with symmetrically arranged laterals i.e. laterals of equal lengths and evenly distributed. Then observations were made with unsymmetrical case, that is, laterals are only on one side. This affects the shape of the draw down curve.

(e) Relationship of discharge with area of openings:- The perforation areas used were 12.5%, 25%, 30% and 35% of the total surface of the laterals. Graphs are plotted showing the relationship between % opening and discharge for a certain arrangement of the laterals.

The large area of exposed perforations in the laterals causes, low inflow velocities which minimize crustation, clogging and sand movement.

(f) Determination of equivalent radius of a vertical well for unsymmetrical case :- For a particular arrangement of laterals we found out the draw down, corresponding discharge in the drain pipe as well as the draw down in the piezometers which are at specific distance from drain pipe. We can draw graphs using these parameters from which the equivalent vertical well radius can be determined.

2.4 EXPERIMENTAL PROCEDURE

(i) After filling the tank with sand, water is supplied to the inlet.

(ii) Level of water is maintained constant in the tank. Excess water flows out through the outlet.

(iii) The regulator connected to the drain pipe is opened.

(iv) When the regulator is opened the water level decreases in tank. By increasing the inlet discharge, level in the tank is maintained constant.

(v) Discharge is measured by measuring rise in water level in a measuring tank.

(vi) Piezometric heads are noted from the glass tubes mounted on a wooden board and connected by plastic pipes to the piezometric tubes.

(vii) Experiment is repeated for different discharges.

(viii) Initially all the laterals are fitted to the drain pipe with their openings to the drain pipe plugged. However, only those laterals which are to be operative are made to function by unplugging the opening connecting the lateral to the drain pipe.

(ix) For finding the equivalent radius of vertical well in unsymmetrical cases, circular cages of different percentage of lateral lengths are used.

(x) For different discharges draw down was measured, with constant water level in the tank.

(xi) To investigate the effect of percentage area of opening on the discharge, measurements were made of discharges and draw down in the drain pipe by using laterals having different areas of opening.

CHAPTER 3

3.1 HANTUSH METHOD

Theoretical analysis of collector wells is fairly complicated. One approach is to treat a collector well as a partially penetrating vertical well. M. Hantush (9) has used this approach in obtaining a theoretical solution for collector well problems. His studies include cases of collector wells with symmetrically located laterals near a stream bed, under a stream bed, etc. The following analysis for the case of collector wells under a stream bed is reproduced for ready reference.

For the case of a collector well under stream bed if the capacity of a stream channel is large compared to the maximum diversion of ground water, the slope of its surface may be neglected If it is assumed that the percentage of the discharge of a collector well that originates from storage in the island portion of aquifer is small relative to that which originates from induced infiltration into the aquifer beneath the stream bed, it may be assumed that the banks of the effectively infinite and fairly straight stream are vertical impermeable planes

that cut completely through the aquifer, hence the method of images may be used to obtain draw down distribution around the collector well under stream beds. The following formalae given by Hantus is valid for $a > 0.5\ (b+r_c+l')$. Also the laterals and their images form four or more symmetrically located laterals. (Refer to Figure 11)

For $t > \frac{5b^2}{\nu}$, draw downs can be estimated from the following equation.

$$Sc/(Q/8\pi klN) = \log \frac{\left[1-\cos\pi\,(2Z_1+r_w)/2b\right]\left[1+\cos\pi\,(r_w/2b)\right]}{\left[1+\cos\pi\,(2Z_1+r_w)/2b\right]\left[1-\cos\pi\,(r_w/2b)\right]}$$

$$+ 16/\pi \sum_{n=0}^{M'} \left[\frac{1}{(2n+1)}\right] \Big\{ L\left[(2n+1)\quad l/2b,\ 0\right]$$

$$+ L\left[(2n+1)\pi\ (l'+r_c)/2b, 0\right] - L\left[(2n+1)\pi\, r_c/b,\ 0\right]$$

$$- \pi/2 + 2(N-1)\ \left[L\left[(2n+1)\ \pi l'/2b,\ 0\right]\right]$$

$$- L\left[(2n+1)\ \pi r_c/2b,\ 0\right]\Big]\Big\}\ \sin\left[(2n+1)\pi\ (Z_1+r_w)/2b\right]$$

$$\sin\ \left[(2n+1)\ \pi Z_1/2b\right] \qquad (3-1)$$

This equation is valid for steady case where

r_c = radius of drain pipe

r_w = radius of laterals

N = No. of laterals.

M' = is an integer such that it is greater than $.5b/rc$

$L(u\pm W)$ = function defined by

$$L(u,\pm W) = -L(-u, \pm W) = \int K_o\left(\sqrt{w^2+y^2}\right)\, dy$$

as a special case $L(u,0) = -L(u,0)$

$$= \int_{\infty}^{0} K_o(y)\, dy$$

l'_o = image length of lateral l.

Z_1 = depth of sand above laterals

b = depth of sand bed.

3.2 PETER'S APPROACH

Another approximate method of analysis is given by Y. Peter (25). Making the following assumptions he arrived at an approximate solution as follows :

ASSUMPTIONS:

(1) The flow into the laterals is linearly distributed.

(2) The entrance area in the lateral for the entry of water is sufficiently large.

(3) Friction losses in the laterals are small.

(4) Water level over the pipes is large compared with the surface depression.

The first assumption leads to the following equation (Refer to figure 12).

$$\frac{Q_o}{L} = \frac{Q_x}{(L-x)}$$

or $$Q_x = \frac{L-x}{L} Q_o \quad - (3-2)$$

where

Q_o = discharge in the central pipe

Q_1 = discharge entering the tip of the lateral

Q_x = discharge flowing in the lateral at a distance x from the axis of the central pipe

1 = length of lateral

Q_x is also the increment in discharge from x = 1 to x = x i.e the increment $\Delta Q = Q_x$.

The above equation is used along with Darcy-Thiem equation for steady state flow. Darcy-Thiem equation can be obtained making the following assumptions :

(1) The flow is horizontal, or the equipotential surfaces are cylinders coaxial with the well.

(2) The velocity is uniform over the depth of flow.

(3) The velocity at the free surface is expressed as $v = - k \frac{dh}{dr}$ instead of $v = - k\, dh/ ds$ where r denotes the radius oriented away from the well and s denotes the flow path then (refer to figure 13)

$$Q_o = 2 \pi r h k \frac{dh}{dr} \tag{3.3}$$

where

Q_o = discharge

k = coefficient of permeability

H_o = water level at outer perimeter at distance

R_o = from the centre of drain pipe

H = water level at distance R from centre of drain pipe

r_w = radius of drain pipe

Boundary conditions are

at $r = R_o$, $h = H_o$

Integrating equation (3.3) and putting the boundary conditions we get

$$\frac{Q_o}{2\pi k} \frac{dr}{r} = h\,dh$$

$$\frac{Q_o}{2\pi k} \Big[\text{Log } r \Big]_r^{R_o} = \Big[\frac{h^2}{2} \Big]_H^{H_o}$$

$$\frac{Q_o}{\pi k} \text{ Log} \left[\frac{R_o}{r} \right] = \left[H_o^2 - H^2 \right]$$

$$Q_o = \frac{\pi k \,(H_o^2 - H^2)}{\text{Log } R_o/r} \tag{3.4}$$

At any point whose coordinates are x, y loss of Q in the sand strata.

$$Q = Q_o \frac{L-x}{L} \quad \text{(See figure 12)}$$

where L = length of laterals

Leaving in sand

$$Q_x = Q_o \left(1 - \frac{L-x}{L}\right) = Q_o \, x/L \tag{3.5}$$

Introducing the flow velocity

$$V_x = \frac{k\,dy}{dx} \tag{3.6}$$

and the flow area

$$A_x = 2\pi y\ (x+r) \tag{3.7}$$

we get,

$$Q_x = Q_o\ (x/L) = 2\pi y\ (x+r).\ K.\ \frac{dy}{dx} \tag{3.8}$$

or $\quad Q_o\ x\ dx = 2\pi\ ly\ (x+r)\ k\ dy.$

or $\quad Q_o\ \frac{x}{x+r}\ dx = 2\pi\ l\ k\ y\ dy$

Integrating both sides we get

$$\int Q_o \left[1 - \frac{r}{x+r}\right] dx = \int 2\pi\ l\ K\ y\ dy + c$$

$$Q_o \left[x - r.\ \log\ (x+r)\right] = 2\pi\ l\ k\ \frac{y^2}{2} + c$$

$$Q_o \left[x - r\ \log\ (x+r)\right] = 2\pi l\ k\ y^2/2 + c$$

when $\quad x = R_o - r,\ y = H_o$ (See figure 14)

$$Q_o \left[R_o - r - r\ \log \left\{(R_o - r + r)\right\}\right] = 2\pi\ lk\ \frac{H_o^2}{2} + c$$

$$Q_o \left[R_o - r - r\ \log\ (R_o)\right] = 2\pi\ lk\ \frac{H_o^2}{2} + c$$

$$Q_o \left[R_o - r - r\ \log\ R_o\right] - 2\pi\ lk\ \frac{H_o^2}{2} = c$$

$$Q_o \left[x - r\ \log\ (x+r)\right] = 2\pi l\ k\ y^2/2 + Q_o \left[R_o - r - r\ \log\ R_o\right] - \pi lk\ H_o^2/2$$

$$\pi l\, ky^2 = Q_o\, x - Q_o\, r \log (x+r) - Q_o\, R_o + Q_o r + Q_o r \log R_o + \pi l k\, H_o^2$$

$$\therefore \quad y^2 = H_o^2 + \frac{Q_o}{\pi l k}\left[x+r - R_o + \frac{\log R_o}{\log (x+r)} \right]$$

$$y = \sqrt{H_o^2 + \frac{Q_o}{\pi k l}\left(x+r-R_o + \frac{\log R_o}{\log (x+r)}\right)} \qquad (3.9)$$

when $x = 0$ let $y = y_o$

then

$$y_o = \sqrt{H_o^2 + \frac{Q_o}{\pi k l}\left(r-R_o + \frac{\log R_o}{\log r}\right)} \qquad (3.10)$$

Equation (3.9) gives the draw down at any distance x from the face of the central pipe, for the given boundary conditions of $y = y_o$ at the face of the central well and $y = H_o$ (non pumping water level) at a distance R_o

These equations may be used to get an approximate draw down profile even when there are more than one lateral. In the next chapter the observed values of draw down are compared with the values computed using equations (3.9) and (3.10).

To find out the relationship between percentage area of opening in laterals, their numbers, length, discharge, draw down, etc., dimensional analysis is done as below

3.3 DIMENSIONAL ANALYSIS:

Let q_l be the flow in a single lateral. The flow depends on the following variables.

A_p, l, T and s_c

where

A_p = Area of openings

l = Length of lateral

T = Transmissibity coefficient

S_c = draw down.

Hence we can write the following equation

$$q_l = f\ (A_p, L, T, S_c)$$

Using the dimensions of each of the variables, we can write :

$$\frac{L^3}{\mathcal{T}} = K_1\ (L^a)\ \ (L^2/\mathcal{T}\ )^b\ \ (L)^c$$

where L = length

$\mathcal{T}$ = time

equating the powers

$$\text{or } 3 = a + 2b + c$$

$$1 = b$$

$$\text{or } a = 3-2 - c = 1 - c$$

$$q_1 = k_1 \, (y^{1-c}) \, (T) \, (S_c^c)$$

where $y = A_p/1$

$$q_1 = k_1 \, (yT) \, (S_c/y)^c = f \, (yT, \; \frac{S_c}{y}) \tag{3.11}$$

assuming that yT is constant and it is a multiplicative constant we can write,

$$q_1 = yT \, f \, (S_c/y) \tag{3.12}$$

$$\therefore \quad \frac{q_1}{yT} = f_1 \, (S_c/y) \tag{3.13}$$

The above equation represents in a non dimensional way the relationship between the various parameters, namely q_1, A_p, 1, s_c, and T. The actual relationship can only be obtained by conducting experiments. This has been done and the results are given in appendix - 1. Using these results the above equation is represented graphically. This will be discussed in the next chapter.

CHAPTER 4

4[illegible] RESULTS AND DISCUSSIONS

4.1 Appendix 1 gives the observed piezometric levels for various experiments conducted. Fig. 15 gives the position of the tappings of the piezometric tips in the experimental setup. In the case of symmetrical arrangement of laterals we can take any one cross section to represent the head distribution because of symmetry. However, it is likely that there will be a slight difference in the piezometric readings at different cross sections because of the curvilinear nature of the equipotential lines. Therefore an average value of the piezometeric reading is used for comparison with the computed value. Some typical calculations are shown below to indicate the method of averaging that is used.

(i) Given the following values;

$x = 65.02$ cm

$Q = 390\ cm^3/sec.$

Arrangement of lateral - 8 laterals (Long), 6" above bed.

The observed values of piezometric heads are as below (See Appendix 1 and Figure 15).

(i) Cross section 1-1	110.00 (in piezometer No.24 f)	108.40	(in piezometer No. 42 B)
(ii) Cross section 2-2	109.00 (in pies No.18f)	107.80	(in piezometer No. 36 B)
(iii) Cross section 3-3	110.00 (in pizo No.45)	109.00	(in piezometer No. 30 A)
	SUM	654.20 cm.	
	AVERAGE	109.20 cm	

(ii) Similarly for x = 32.5, cm, Q = 2225 cm^3/sec and for 4 laterals in 3 tiers average value of piezometric head = 106 50 cm

Table 4-1 gives all the mean observed values as computed above.

The above observed values are compared with theoretical values obtained by using equation (3-9).

$$y = \sqrt{H_o^2 + \frac{Q_o}{\pi lk}\left(x+r-R_o+\frac{\log R_o}{\log(x+r)}\right)} \qquad (3.9)$$

(repeated)

A few specimen calculation are shown below to indicate how the theoretical values are computed by using the above equation. The values used are the same as that for which the mean observed values were determined above.

SPECIMEN CALCULATIONS

For eight laterals, 6 inch above bed (L=76.2 cm)

$$y = \sqrt{H_o^2 + \frac{Q_o}{\pi l k}\left(x+r-R_o+\frac{\log P_o}{\log(x+r)}\right)}$$

H_o = 112 76 cm

Q_o = 390 cm^3/sec.

L = 76.2 cm

x = 65.02 cm

r = 10.16 cm

R_o = 91.44 cm

$$y = \sqrt{(112.76)^2 + \frac{390}{\pi \ .03x76.2}\left(6502+10.16-91.44 + \frac{\log 91.44}{\log 75.18}\right)}$$

$$\simeq \sqrt{12769 - 274}$$

$$\simeq \sqrt{12495} \text{ cm}$$

$$\simeq \sqrt{111.80 \text{ cm}}$$

(The value obtained by the computer is 112.30)

(2) For 4 laterals in all the three tier (L=76.2 cm)

Q_o = 2225 cm^3/sec.

x = 32.51 cm

L = 76.2 cm

r = 10.16 cm

R_o = 91 44 cm

H_o = 112.76 cm

Using the above equation

$$y = \sqrt{(112.76)^2 + \frac{2225}{(.03)76.2} \left(32.51+10.16-91.44 + \log \frac{91.44}{\log 42.67}\right)}$$

$$\simeq \sqrt{12769 + 31.2\,(-47.57)} \text{ cm}$$

$$\simeq \sqrt{11289}$$

$$\simeq 105.00 \text{ cm}$$

(The value obtained by the computer = 107.177)

A computer program which determines the draw down for various discharges and for various arrangement of laterals is enclosed as Appendix - 2. Table 4-3 gives a comparison of the observed values and the computed values.

We can see from the table (4-3) that the observed values tally with computed values when the discharges are low and when the distances are large. How-ever when the discharges are large the difference is significant. There may be several reasons for this discrepancy. A few of them are indicated below :

(i) When the discharges are small the flow is laminar. The equation (3-9) assumes laminar flow. Hence the discrepancy is small when the discharge is small.

(ii) When discharges are large the flow is likely to become non linear and hence equation (3-9) may not be valid.

(iii) It may be seen that equation (3-9) is derived assuming only one lateral. The same equation is used for finding the discharge even when there are more than one lateral by simply multiplying the discharge for one lateral by the number of laterals. This is not strictly true. When the laterals are arranged around the circum-

TABLE 4-1

COMPARISON OF OBSERVED VALUES OF DRAW DOWN AND VALUES CALCULATED FROM PETER'S EQUATION AT DIFFERENT DISTANCES FROM CENTRAL PIPE FOR DIFFERENT DISCHARGES

FOR TWO LATERALS ARRANGED SYMMETRICALLY (Length of each lateral = 76.2 cm

Discharge $cm^3/sec.$	DRAW DOWN AT							
	16.26 cm		32.51 cm		48.77 cm		65.02 cm	
	Observed value (cm)	Calculated value (cm)	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
342	106.7	105.829	107.74	107.621	107.72	109.395	109.40	111.142
510	105.8	102.252	107.85	105.005	108.33	107.703	109.70	110.339
780	101.0	96.225	104.00	100.658	105.3	104.927	108.59	109.035

FOR FOUR LATERALS ARRANGED SYMMETRICALLY (Length of each lateral = 76.2 cm)

Discharge $cm^3/sec.$	DRAW DOWN AT							
	16.26 cm		32.51 cm		48.77 cm		65.02 cm	
	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
338	106.00	109.390	105.80	108.251	107.00	111.10	109.00	111.963
463	106.80	108.117	107.00	109.308	108.00	110.493	109.60	111.667
1045	105.50	101.981	105.00	104.808	106.34	107.576	108.20	110.279

FOR EIGHT LATERALS ARRANGED SYMMETRICALLY (Length of each lateral = 76.2 cm)

Discharge cm^3/sec	DRAW DOWN AT							
	16.26 cm		32.51 cm		48.77 cm		65.02 cm	
	Observed value (cm)	Calculated (cm)	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
390	108.10	110.93	108.80	111.03	108.80	111.20	109.20	111.40
1010	105.80	110.22	106.80	110.41	107.00	110.73	110.00	111.10
2160	101.40	105.69	101.10	106.44	101.80	107.72	108.40	109.18
2860	96.00	105.54	96.00	106.30	100.20	107.62	108.00	109.11

FOR FOUR LATERALS IN ALL THE THREE TIER (Length of each lateral = 76.2 cm)

Discharge cm^3/sec.	DRAW DOWN AT							
	16.26 cm		32.51 cm		48.77 cm		65.02 cm	
	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.	Obs.	Cal.
600	107.00	109.19	108.00	109.50	108.00	110.04	110.00	110.65
1353	106.20	105.86	107.20	106.59	108.00	107.84	108.50	109.25
2225	102.00	101.84	106.50	105.09	107.00	105.21	108.40	107.58
3460	100.00	95.96	103.80	97.99	105.00	101.43	106.80	105.22
4400	98.50	91.35	102.00	94.04	104.00	98.54	106.50	103.43

TABLE 4-2

COMPARISON OF DISCHARGE FOR VARIOUS DRAW DOWNS

S_c Cms	DISCHARGES (CM^3/SEC)					
	2 laterals		4 laterals		8 laterals	
	Long Pipe	Small Pipe	Long Pipe	Small Pipe	Long Pipe	Small Pipe
20	368	340	620	584	922	900
30	563	530	873	786	1240	1208
40	728	670	1097	990	1590	1510
50	863	747	1300	1143	1870	1783
60	970	835	1474	1310	2140	2020

TABLE 4-3

EFFECT OF ELEVATION OF LATERALS ON DISCHARGE

S_c Cms	DISCHARGES (CM^3/SEC)										
	6" above the bed				12" above the bed			18" above the bed			
	2	3	4	5	2	3	4	2	3	4	5
20	262	368	465	600	258	360	470	260	360	464	610
30	368	515	650	825	364	520	650	360	504	650	820
40	475	650	825	1020	470	655	830	468	652	820	1025
50	562	756	970	1190	555	750	972	560	751	972	1180
60	640	873	1095	1350	635	870	1095	632	871	1102	1360
70	709	875	1220	1492	715	882	1225	703	874	1125	1495

ference of a central collector well the flow is radial, whereas the flow assumed in the case of one lateral is a plane flow

4.2 The effect of length of laterals is not very significant so long as the boundary is quite distant. Two different lengths were used in performing the Experiment 76.2 cm and 38 cm It is found that for the same draw down discharge decreases but by a small amount as compared to the length of laterals. For example at a draw down of 40 cms, the discharge in the case of 76 cm length of lateral is 728 cm^3/sec. & 670 cm^3/sec. for 38 cm length of lateral for the case of 2 laterals arranged symmetrically. Table 4-2. gives a comparison for other draw downs. Fig. 4(a) and 4(b) show a plot of discharge V/S draw down for various numbers and arrangement of laterals.

4.3 An experiment was also performed to see the effect of elevation on the discharge. Fig. 5(a), 5(b), 5(c) show discharge V/S drawdown in the central pipe of the collector well for various locations of the laterals. Table 4-3) gives a comparison of the effect of height at which laterals are mounted.

It can be seen from the above table that there is not much effect on discharge when laterals are located at different heights from the bed.

4.4 It has also been found out from experiments that discharge increases with increase in the number of laterals. As there is negligible effect of elevation of the laterals, we can increase the discharge by increasing the number of laterals proportionately but when several tiers are operated simultaneously there is some interference effect. See fig 16 For symmetrical cases i.e. length of laterals as well as their spacing is same, the water surface profile is symmetrical but for unsymmetrical cases the shape of water surface profile gets distorted. This phenomenon may be because of the fact that water in the main pipe comes only from one side, other side is less affected.

4.5 An experiment was also performed for various percentage area of openings of the lateral surface. Four percentage of areas of openings were used(12.5%, 25%, 30%, 35%), for each percentage of opening, discharges were determined for the drawdowns of 15 cm, 25 cm, 30 cm, 40 cm. The results are shown in figure 6. The length of laterals were 76.2 cm. Four laterals were arranged symmetrically as shown in Fig. 6. It can be seen from the figure

that the curves tend to become horizontal after about 35% of opening for all draw downs We can therefore conclude tentatively from this that more than about 35% opening will not result in any increase in discharge for the same draw down.

4.6 In practice collector wells are analysed by treating them as vertical wells of a certain equivalent radius. By equivalent radius we mean that radius of the vertical well which will give the same discharge as that in a collector well at the same draw down. These equivalent radii are determined experimentally for various arrangements of the laterals. Figure 7 shows the discharge V/S draw down for vertical wells of different diameters. Figure 4(a) and 4(b) give discharge V/S drawdown for collector wells. By superposing figure 7 on figure 4(a), we see that curves c_1 (for n = 2), c_2 (for n = 4) and c_3 (for n =8) envelopes between 7.5 inch and 12.5 inch curve. When the number of laterals becomes large the collector well can be replaced by an equivalent vertical well of about 80% diameter but as the number of lateral decreases the equivalent vertical well diameter depends upon its number. Similarly in the case of unsymmetrical arrangement of laterals, by superposing Fig 7 on fig 5(c), the following conclusion can

be drawn :

On Fig. 7 the dotted line shows the possible curve that we obtain if we have a vertical well of diameter 7.1/2 inch. The two curves A and B (A refers to the curve for the 7.1/2 inch dia well and B refers to 10 inch dia well) between them are seen to envelope roughly the curves P, Q, R and S (Refers to the curve for 2 laterals, Q for 3 lat, R for 4 lat and S for 5 lat) till about a draw down of 12.5 cm. Hence we can say that upto this draw down we can replace the collector well with a vertical well of diameter between 50% to 67% of the length of laterals. These percentages are obtained as below:

Length of laterals = 38.1 cm.

Equivalent diameter of the vertical well - 7.5 inch to 10 inch.

Hence the percentage is $\frac{7.5 \times 2.54}{38.1} = 50\%$

and $\frac{10 \times 2.54}{38.1} = 67\%$.

Beyond a draw down of 12.5 cm it is seen that the curves for vertical wells rise steeply upwards whereas for collector wells the curve flatten out gradually. This difference in trend again is possibly because of the

excessive draw down. In the case of unconfined aquifer we usually restrict the draw down to small percentage of the initial saturated thickness of the aquifer for purpose of analysis.

4.7 The relationship between the percentage area of opening provided and other parameters are represented by equation (3-12). In other words to find the actual form of the equation, experiments were conducted with varying percentages of openings and the results are presented in figure 8. By fitting an equation to the curve representing n = 2 laterals, the following equation is obtained.

$$\frac{Q}{yT} = -166 + 108\,\frac{Sc}{10y} - 3.6\left(\frac{Sc}{10y}\right)^2 \qquad (4.1)$$

curves for n = 4 and n = 8 are similar to that for n = 2. We can obtain the equation for any n by considering the equation for n = 2. The following equation represents Q_n when Q_2 is known, other conditions remaining same :

See appendix 3, and fig 9

$$Q_n = Q_2\left[1+0.8\log_e\,(n/2)\right] \qquad (4.2)$$

where Q_n = discharge for the case of n laterals

Q_2 = discharge for the case of 2 laterals.

The way we use equation (4-2) is as follows :

Given values for Sc (draw down), A_p (percent area of opening), L (length of lateral) and T (Transmissibity coeff), we can enter the figure 8 and determine Q for n = 2 (of course from the above figure we can also get Q for n = 4 and n = 8 too). Using the above equation (4-2) we can now obtain Q_n for the same values of parameters given above for any n. For example, for Sc/y = 50, we get $\frac{Q}{yT}$ = 275 from the figure (for T = 3.63 cm^2/sec.) A_p = 12.5% , l = 76.2 cm).

$\therefore$ Discharge for this case comes to be

$$Q_2 = 275\ (y)\ (T) \text{ where } y = \frac{A_p}{L}$$

$$= 275\ \left(\frac{12.5}{76.2}\right)\ (3.63)$$

$$= 164\ cm^3/sec.$$

For the same conditions, if we had 4 laterals, then the discharge would be

$$Q_4 = Q_2 \left[1 + .8 \log_e (4/2)\right]$$

$$= 164 \left[1 + .8\ (0.693)\right]$$

$$= 164\ (1.554) = 255\ cm^3/sec.$$

using this value of Q, if we calculate $\frac{Q}{yT}$ we get

$\frac{255 \times 76.2}{12.5 \times 3.63}$ = 426. The value we get from the figure 8 is about 475. Equation (4-2) is an emperical equation. So it gives only an approximate value of discharge.

4.8 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK :

Collector wells can be used with advantage in situations where vertical wells are not suitable. Such situations arise, for example, in the case of aquifers which are thin and hence do not provide enough length for screens.

In the present work experiments were conducted to determine the effect of various parameters like length of laterals, area of opening, number and arrangement of laterals etc. on the yield or discharge of a collector well. The results have been discussed already.

Analytical treatment of collector wells is difficult. Hantush (9) has given solutions for certain arrangement of laterals. One of the pressing problems in the field of collector wells is to be able to determine the yield when the laterals are unsymmetrical. That is, when the length of laterals are different and when they extend only in a particular direction. One of the methods to

using this value of Q, if we calculate $\frac{Q}{yT}$ we get

$\frac{255 \times 76.2}{12.5 \times 3.63} = 426$. The value we get from the figure 8 is about 475. Equation (4-2) is an emperical equation. So it gives only an approximate value of discharge.

4.8 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK :

Collector wells can be used with advantage in situations where vertical wells are not suitable. Such situations arise, for example, in the case of aquifers which are thin and hence do not provide enough length for screens.

In the present work experiments were conducted to determine the effect of various parameters like length of laterals, area of opening, number and arrangement of laterals etc. on the yield or discharge of a collector well. The results have been discussed already.

Analytical treatment of collector wells is difficult. Hantush (9) has given solutions for certain arrangement of laterals. One of the pressing problems in the field of collector wells is to be able to determine the yield when the laterals are unsymmetrical. That is, when the length of laterals are different and when they extend only in a particular direction. One of the methods to

solve unsymmetrical well problem is by equivalent vertical well radius method. Some experiments were conducted in this direction and the results have been reported above. However more work requires to be done in this direction.

Equations (4-2) has been developed based on dimensional analysis. The validity of this equation should be checked when the number of laterals is greater than 8.

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APPENDIX 3

$$Q_4 - Q_2 = c$$

where c is a constant

$$Q_8 - Q_4 = c$$

$$Q_{16} - Q_8 = c$$

$$Q_{2^i} - Q^{(i-1)} = c$$

Summing we get

$$Q_{2^i} = (i-1)\ c + Q_2$$

where $2^i = n$

or $$i = \frac{\log n}{\log 2}$$

$$Q_2 = 1.0$$

or $$Q(n) = Q_2 \left[\left(\frac{\log n}{\log 2} - 1 \right) c + 1 \right]$$

$$c = .55 \text{ from graph}$$

$$Q(n) = \left[1 + .8 \log_e (n/2) \right] \quad \text{For } n = 2,4,8,16$$

Similarly for unsymm case

$$Q(n) = Q_2 \left[(n-2)\ c + 1 \right]$$

$$c \approx .4 \text{ from graph}$$

or $$Q(n) = Q_2 \left[(n-2)\ .4 + 1 \right]$$

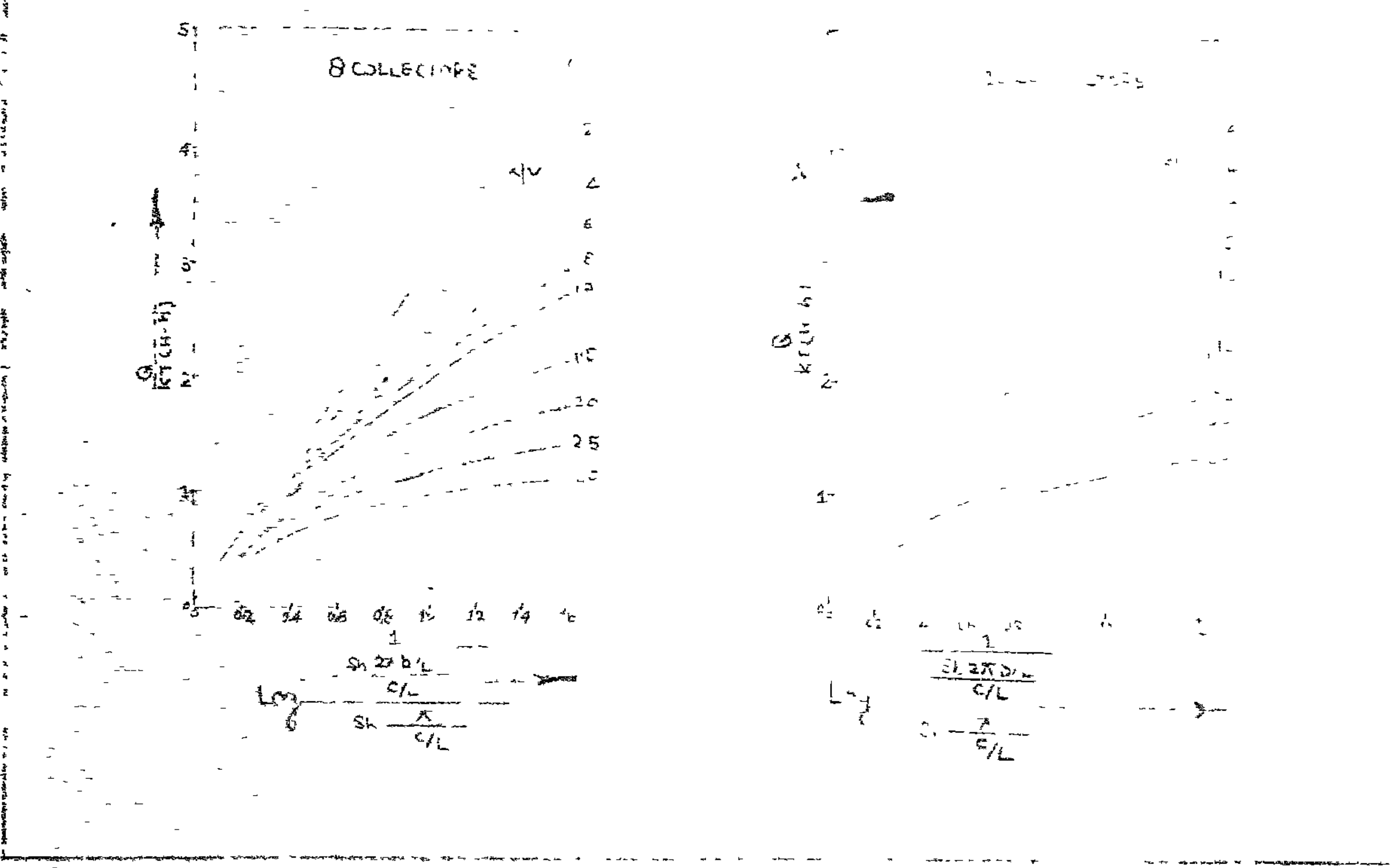


FIG. 4. RELATIONSHIP BETWEEN YIELD AND OTHER PARAMETERS

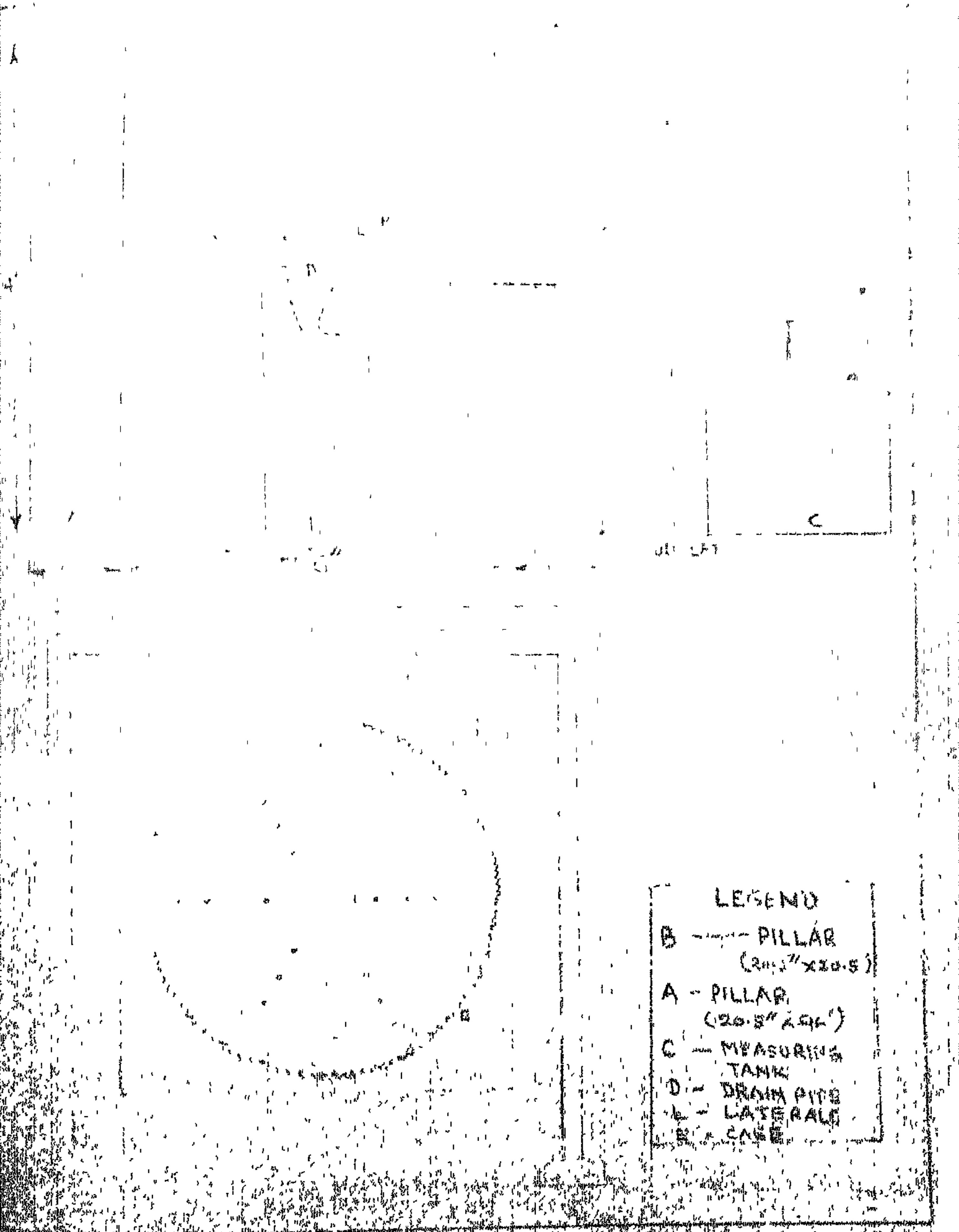
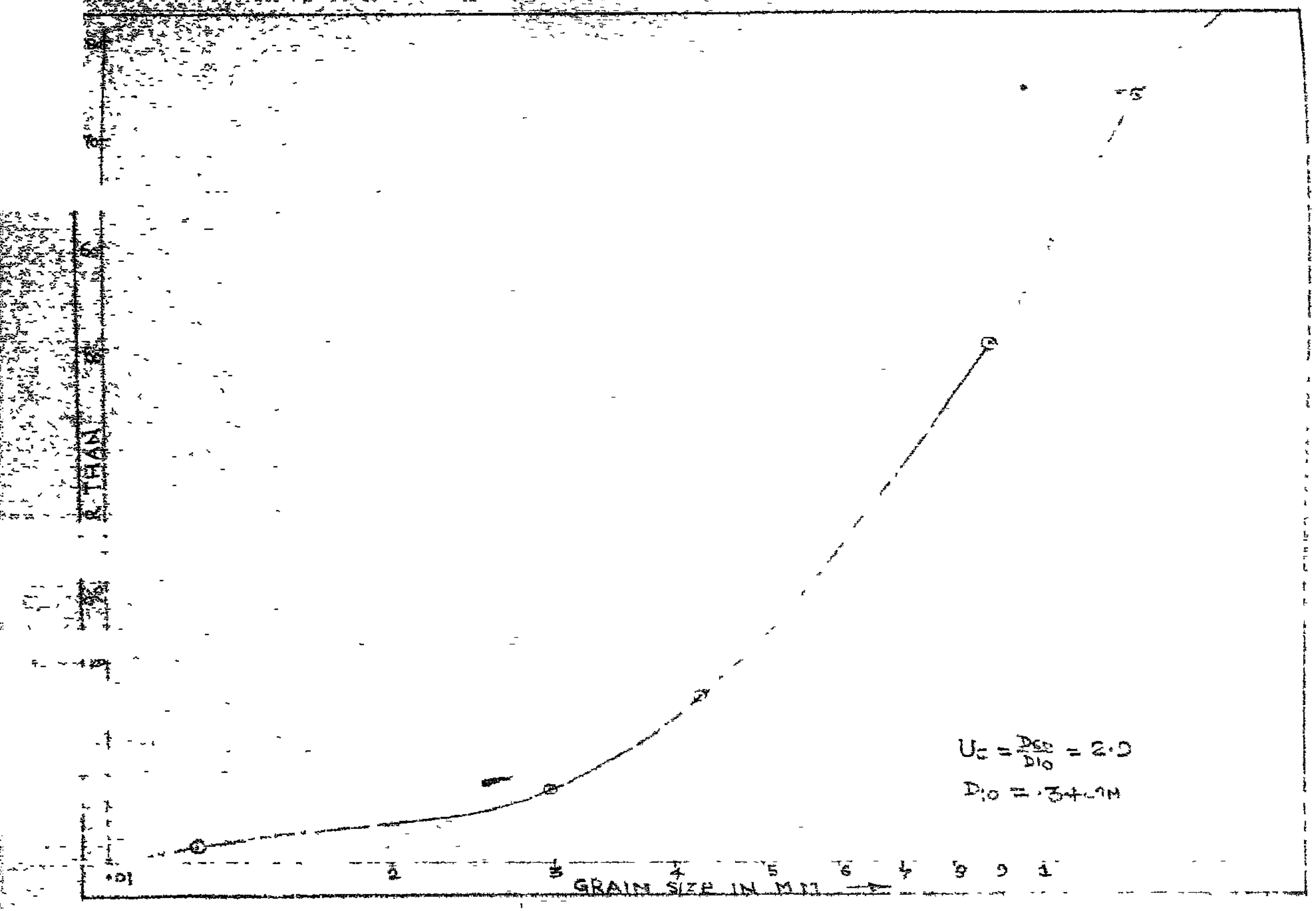
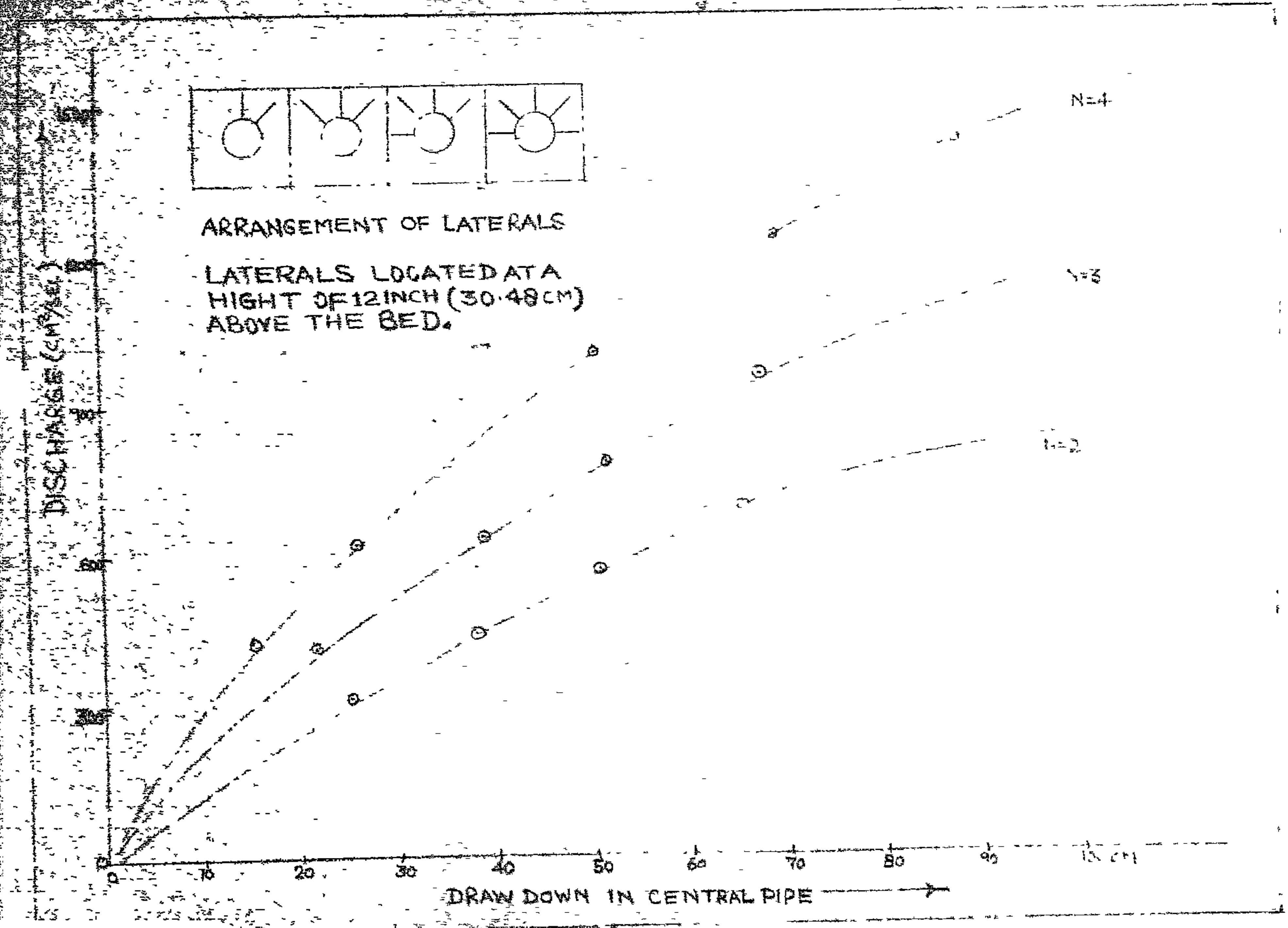


FIG. 3 SCHEMATIC DIAGRAM OF THE EXP SET UP



FIG#3 GRAIN SIZE DISTRIBUTION



EFFECT OF ELEVATION OF LATERALS ON DISCHARGE.

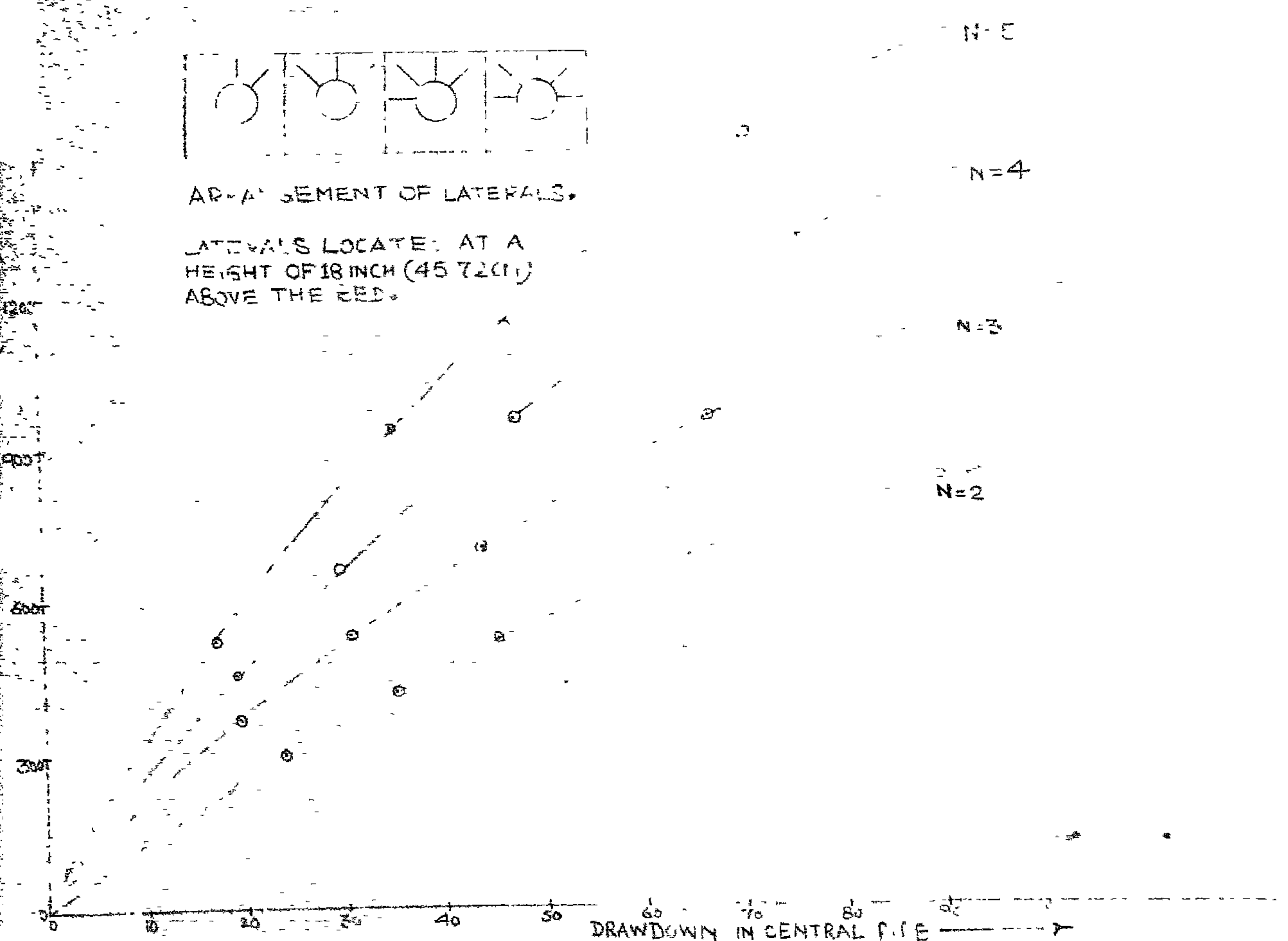
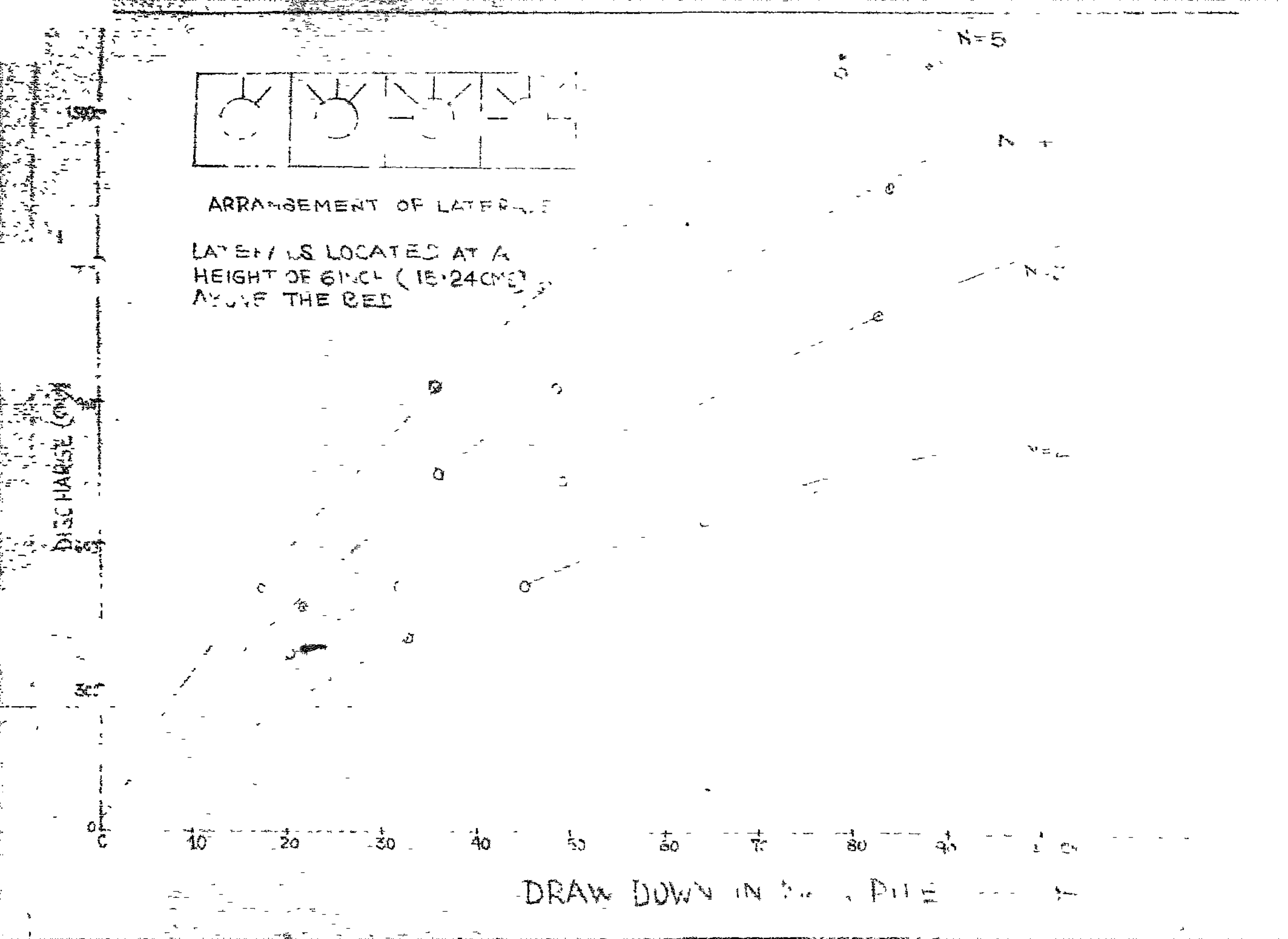


FIG # 5(b) PLOT SHOWING EFFECT OF ELEVATION OF LATERALS ON DISCHARGE.



N=5
ARRANGEMENT OF LAT
HEIGHT OF 6 INCH (15·24 CMS)
THE BED
DISCHARGE
1500
0
10
20
30
40
50
60
80
DRAW DOWN IN

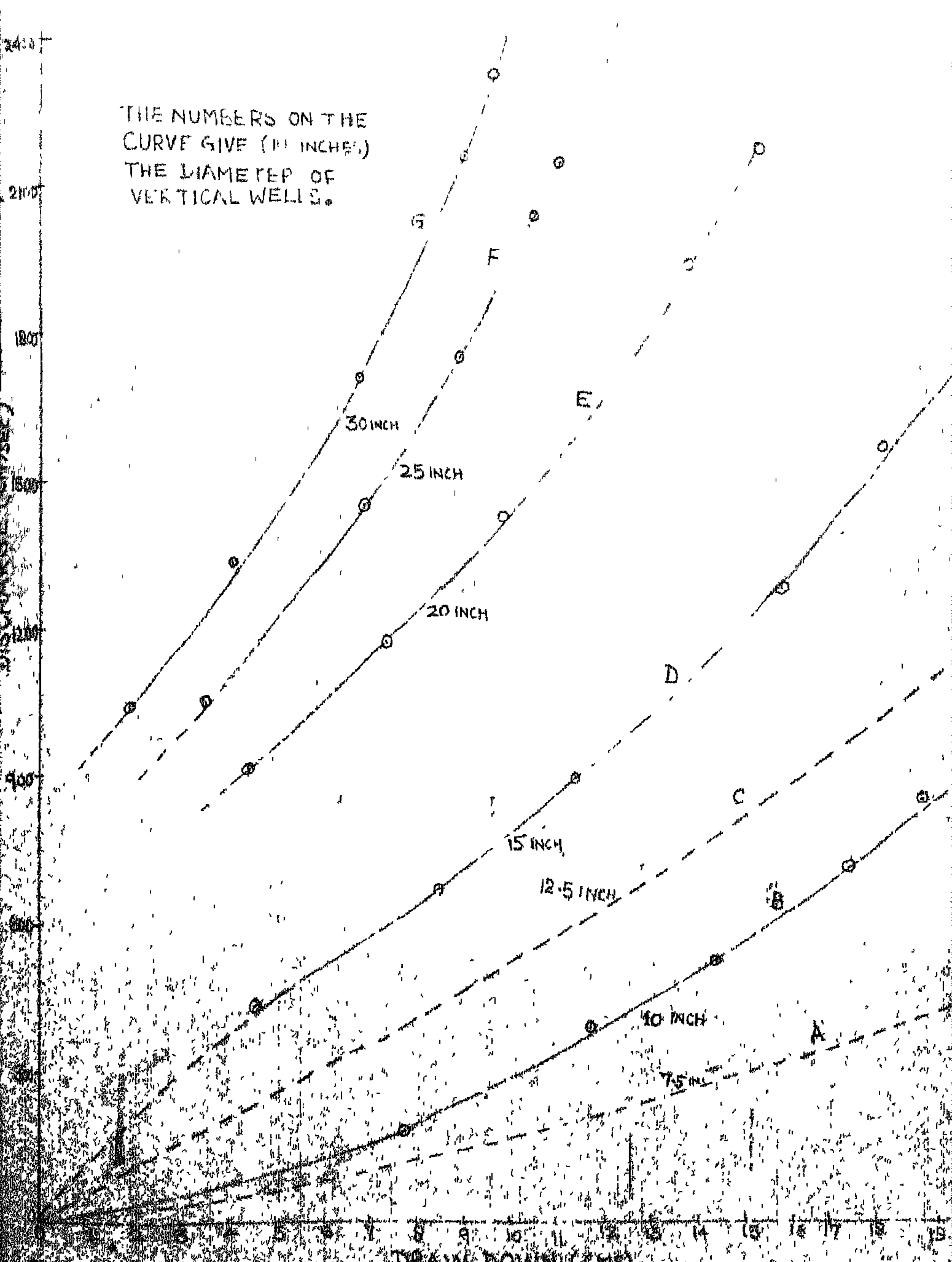
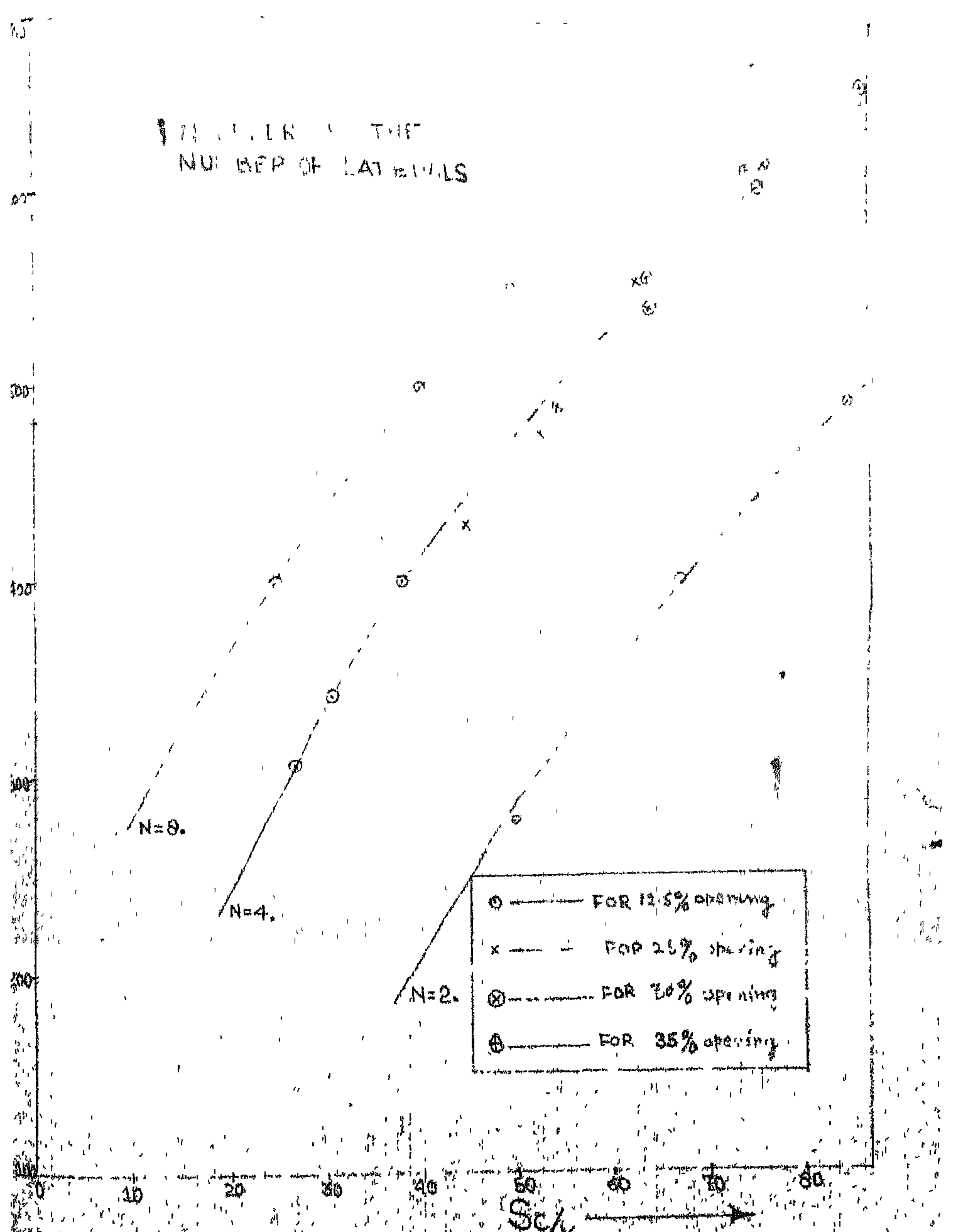


FIG # 7 GRAPH SHOWING DISCHARGE Vs DRAWDOWN FOR VERTICAL



FIG# 9. RELATIONSHIP BETWEEN THE DIMENSIONLESS PARAMETE... FOR VARIOUS PERCENT AREA OF OPENINGS.

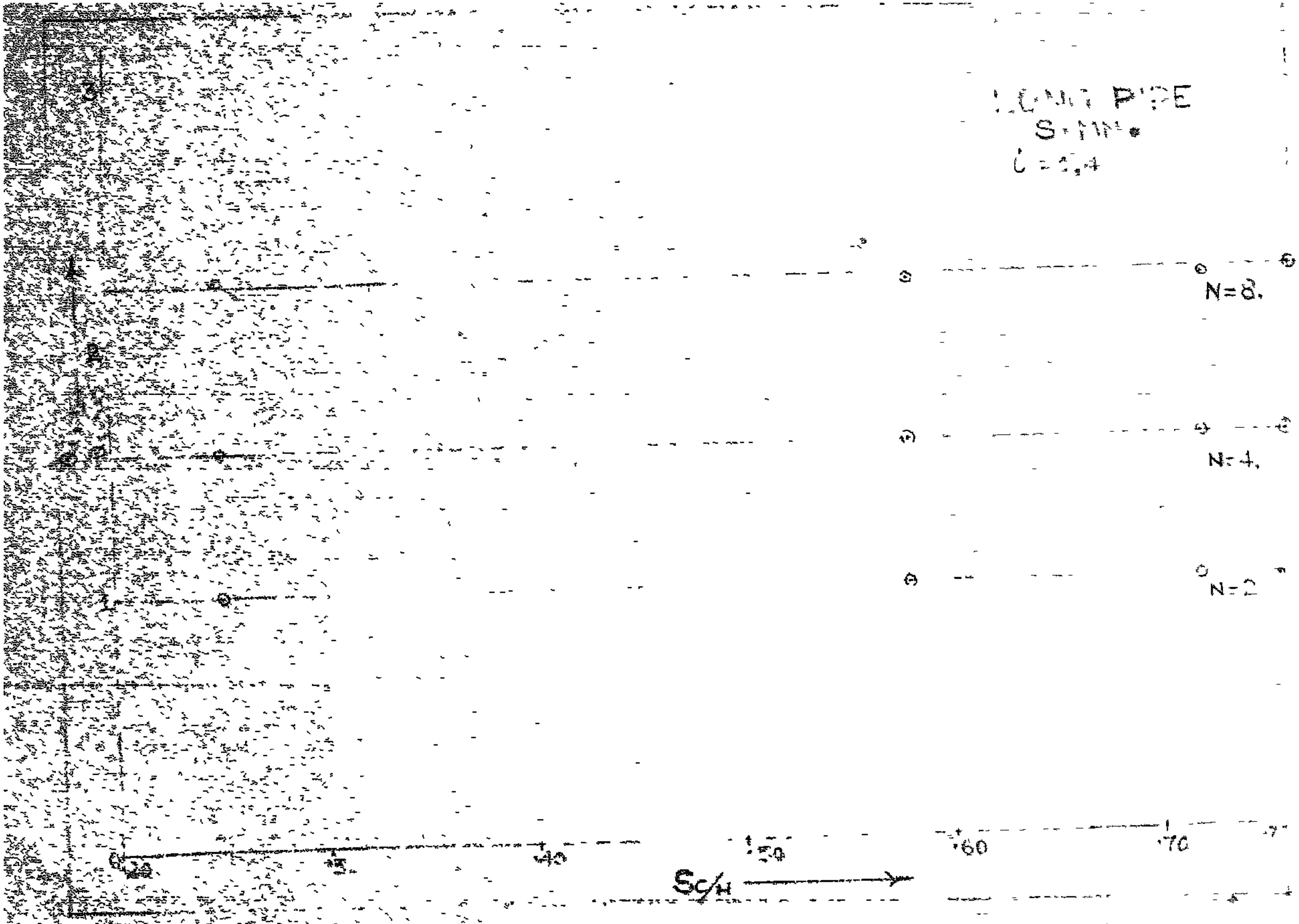
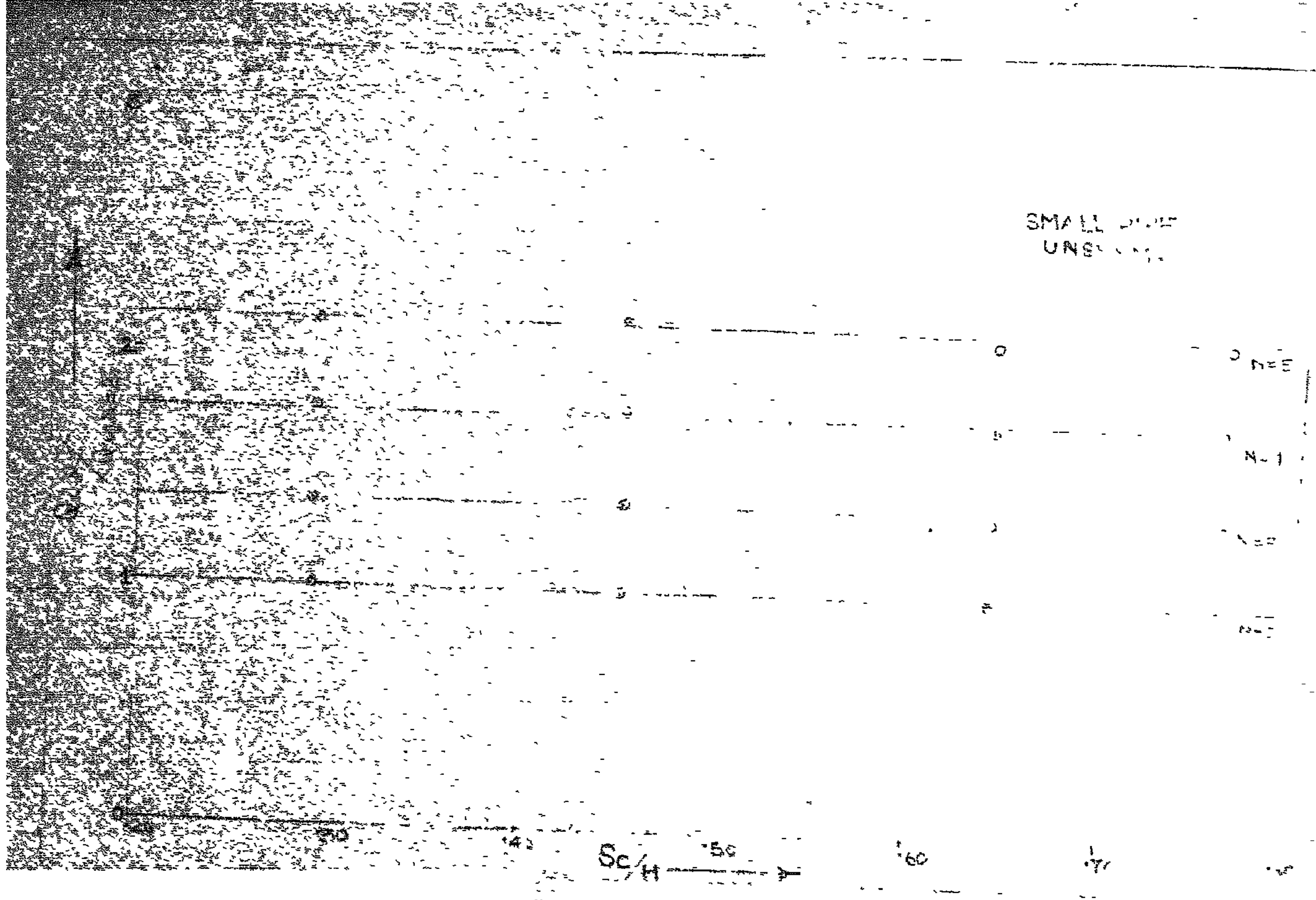


FIG. ... SHOWING ... IN DISCHARGE FOR VARIOUS DRAWDOWNS ... HEAD OF WATER LEVEL.


SMALL
Sc/H
50
60

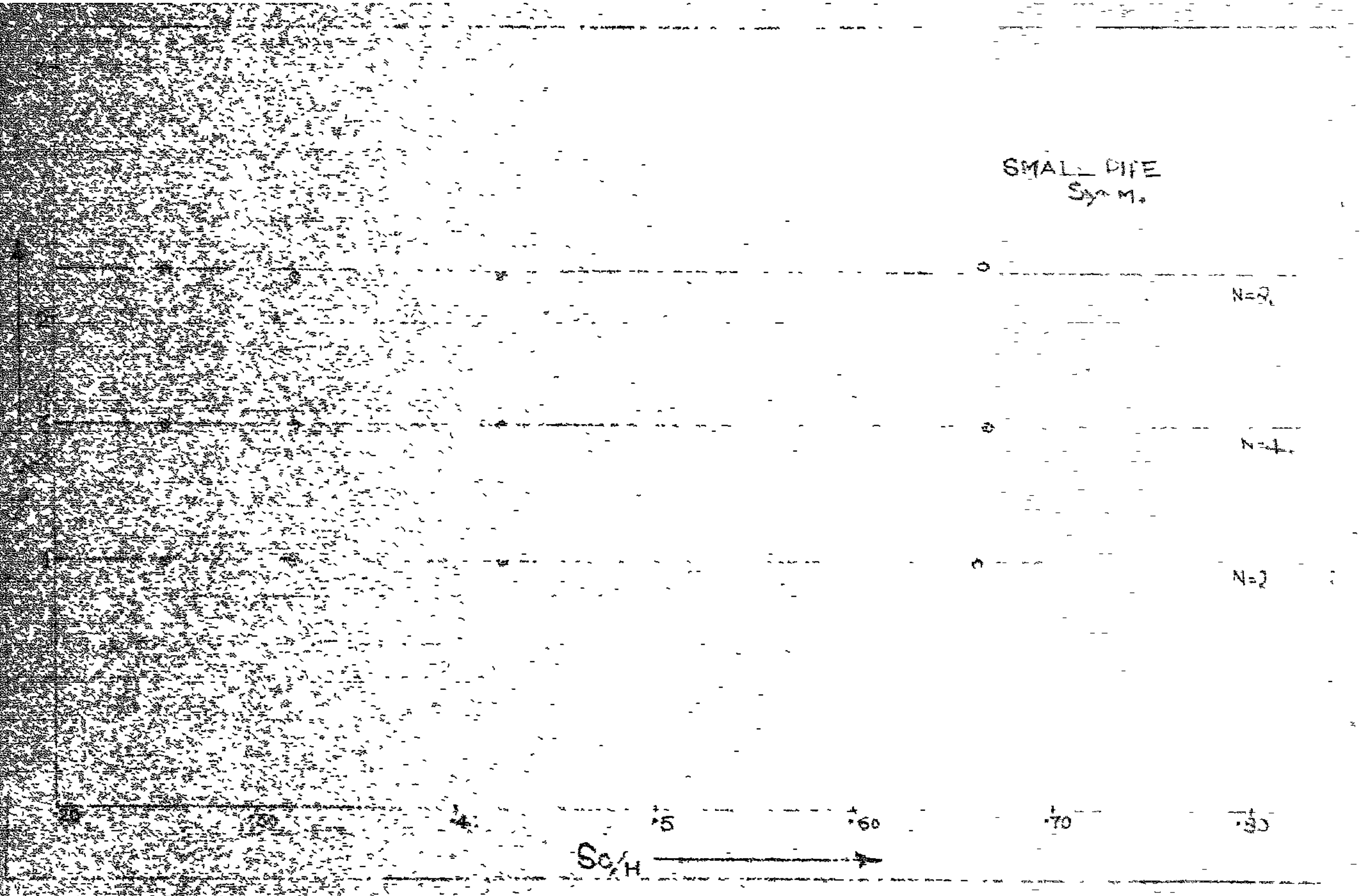
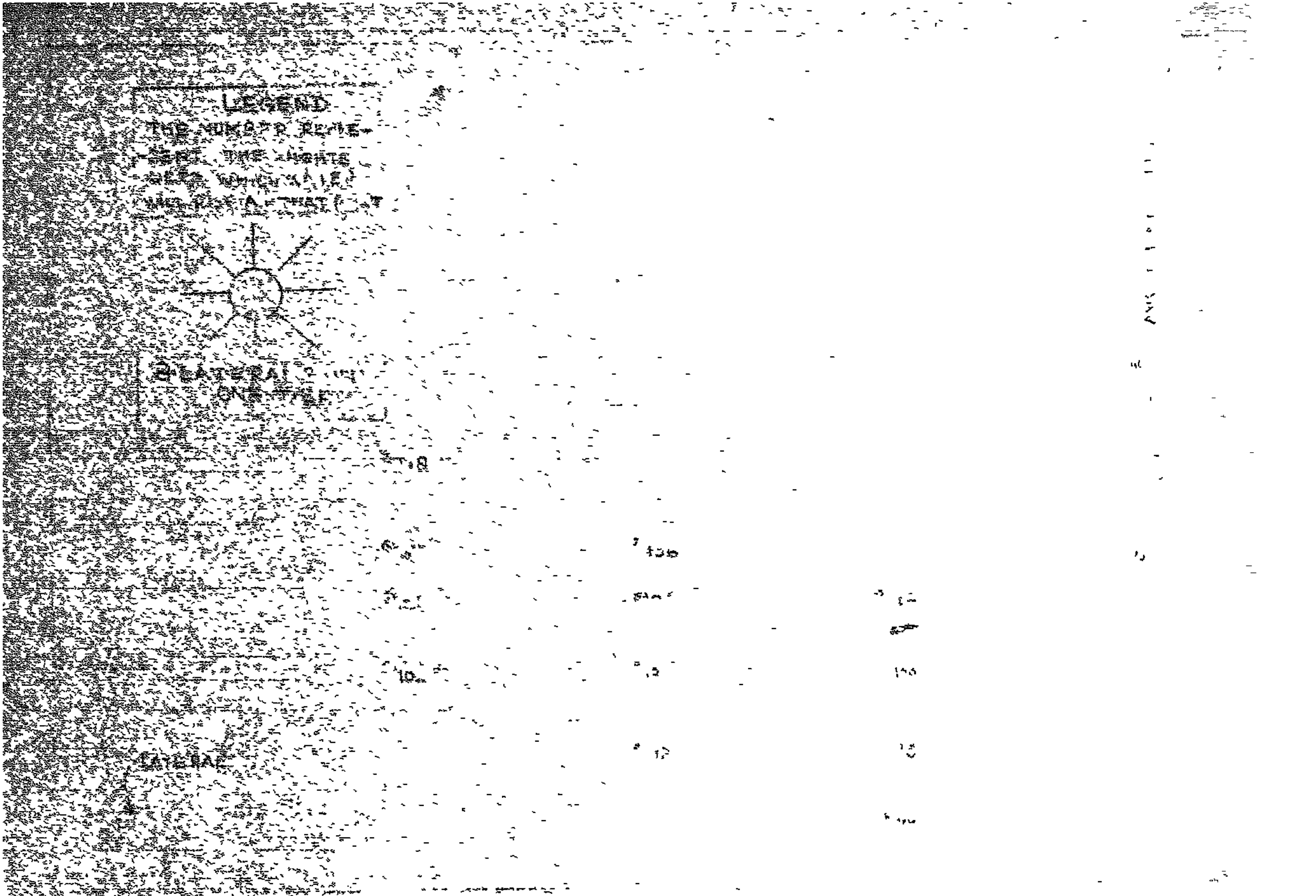


FIG # ... INCREASE IN DISCHARGE FOR VA... DRAW...



... ZOMETRIC HEAD ... 216 ...

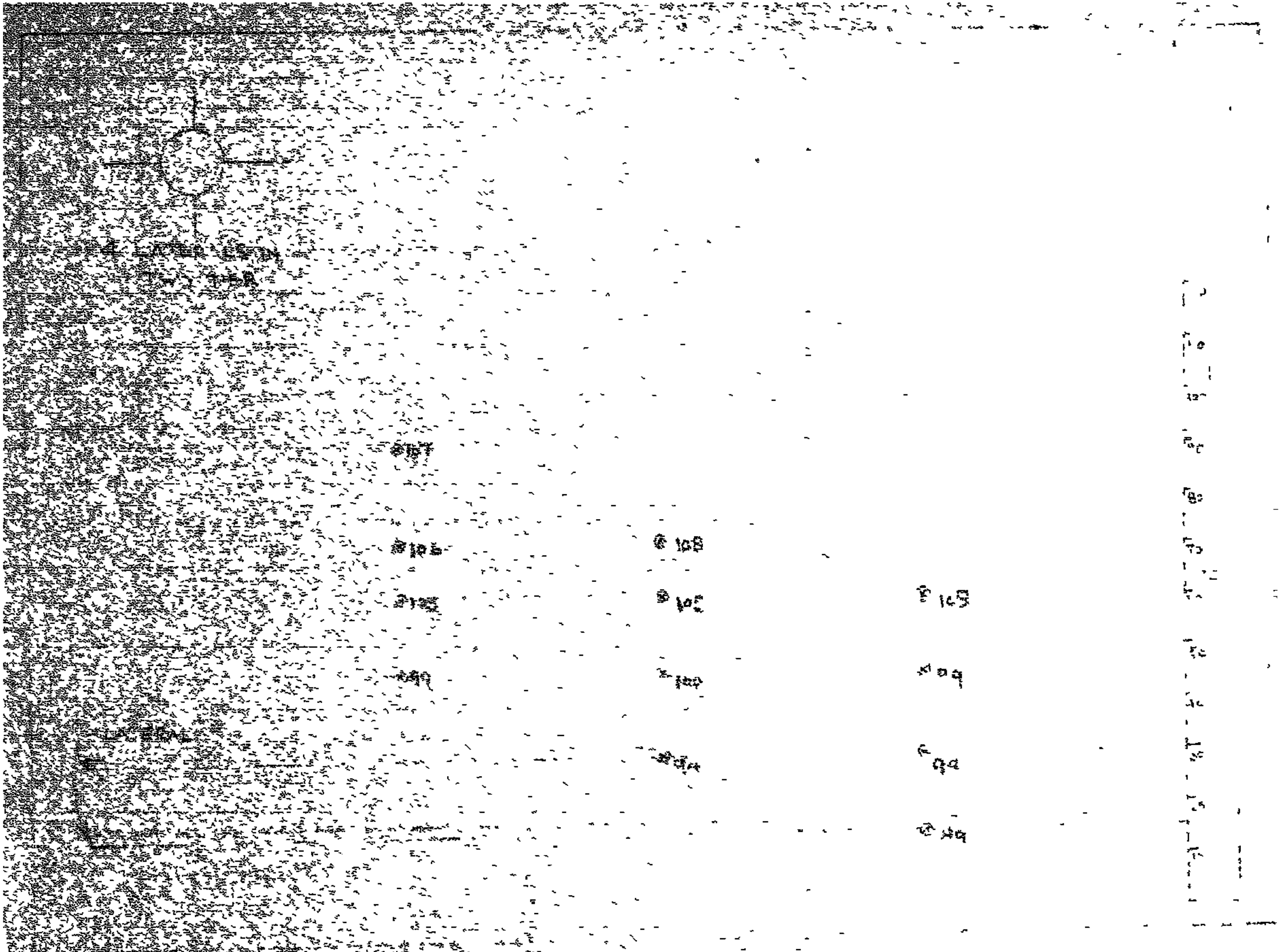


FIG. 10B PIEZOMETRIC HEAD WHEN 224 CM/S ... ARE FLOWING

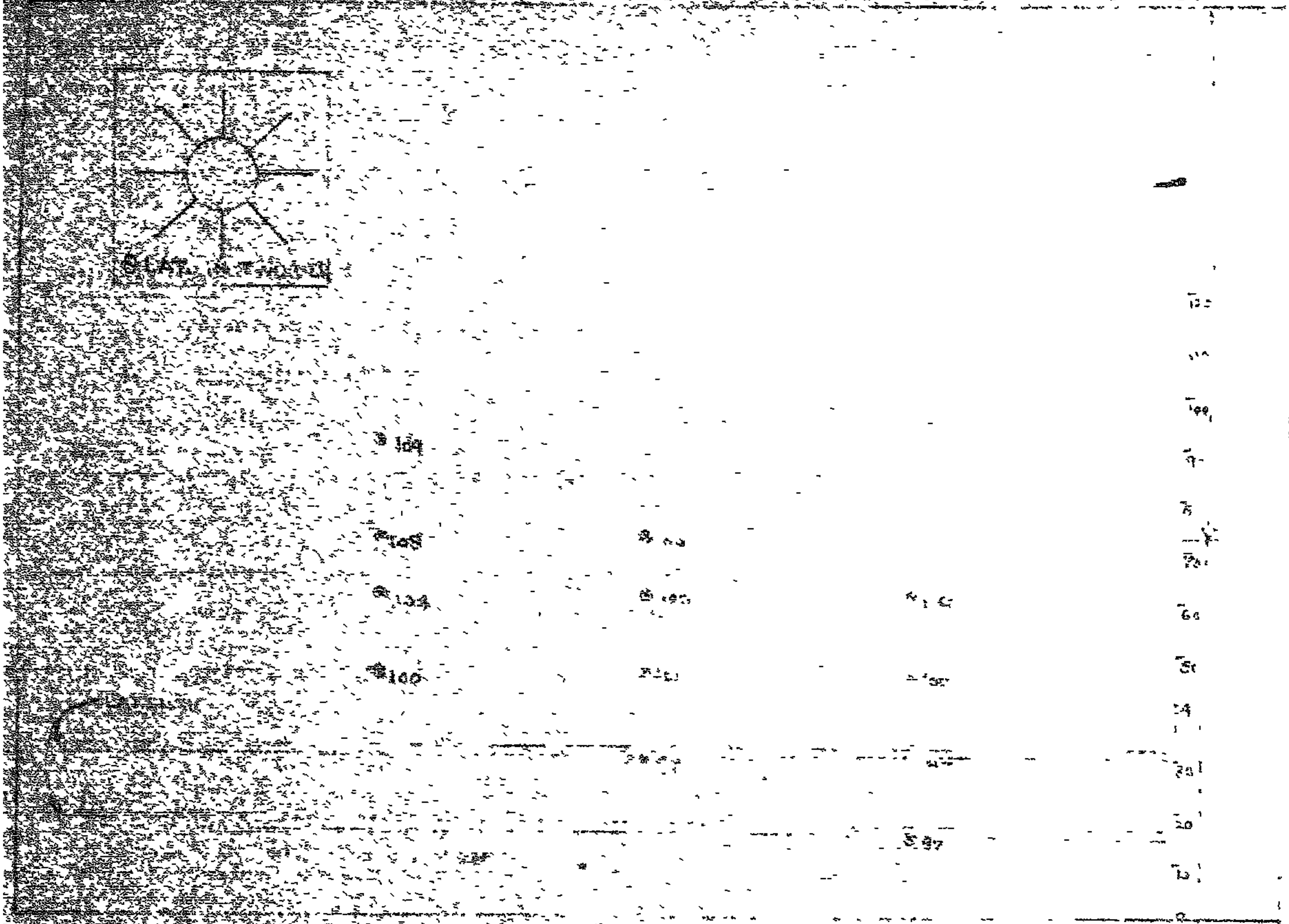
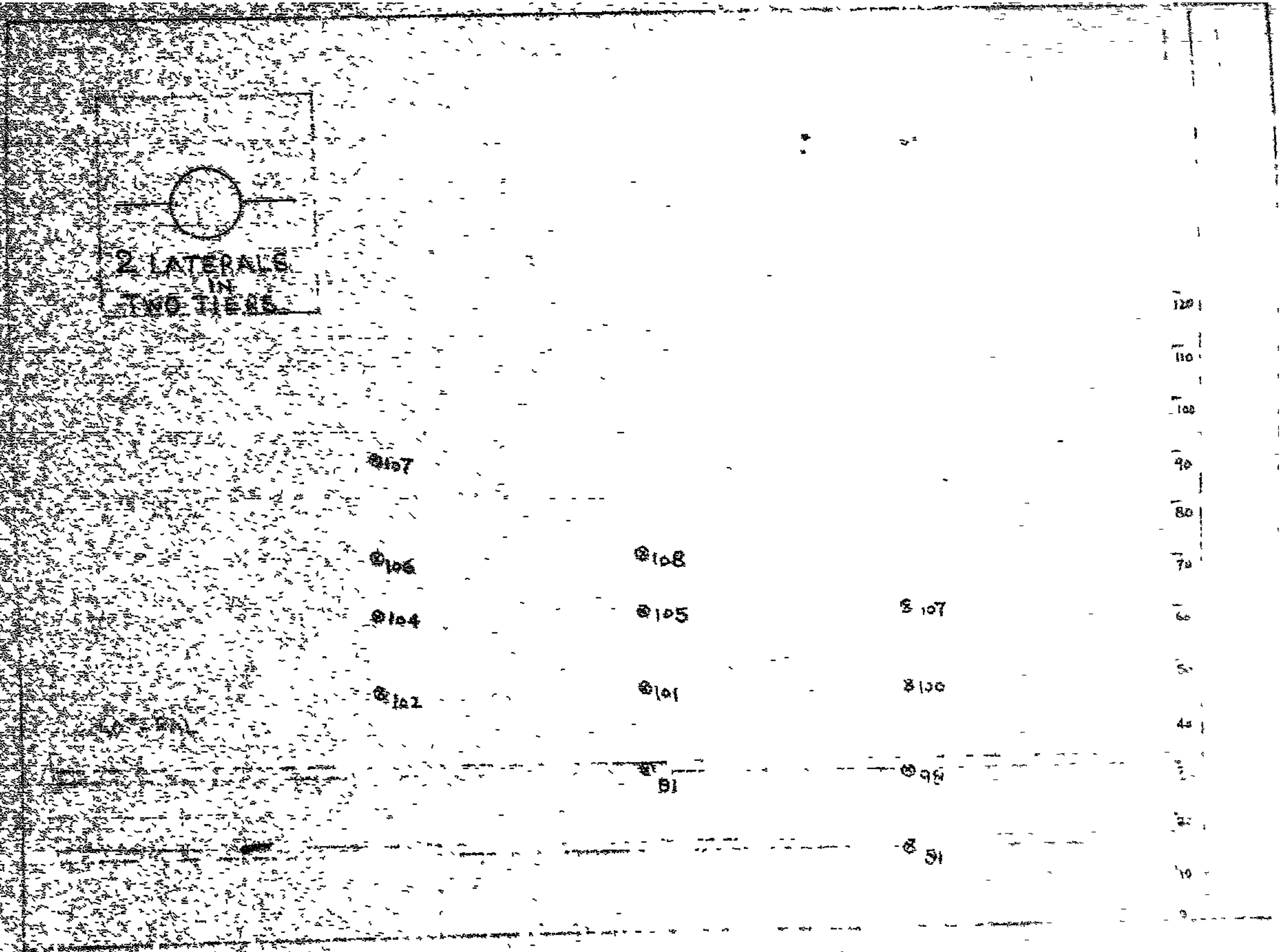
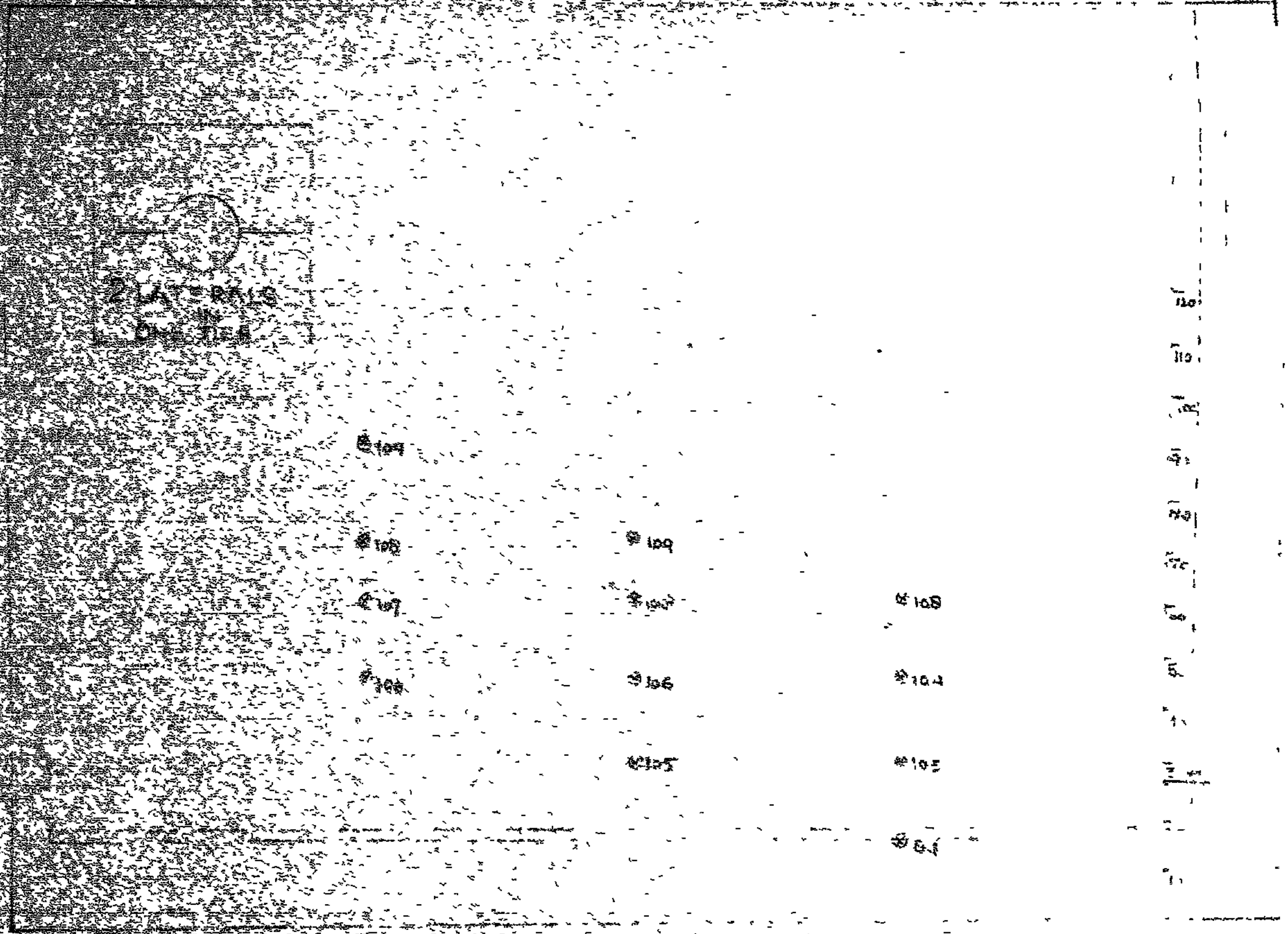


FIG [illegible] HEAT WHEN [illegible] CM [illegible] ARE [illegible]
OUT OF WELL.



FIG# 40DC PIEZOME... ...D WHEN 1630 CM/SECS ARE OUT OF WELL



FIG# 10E. PIEZOMETRIC HEAD WHEN 815 (M³)/ECS ARE FLOWING OUT OF WELL

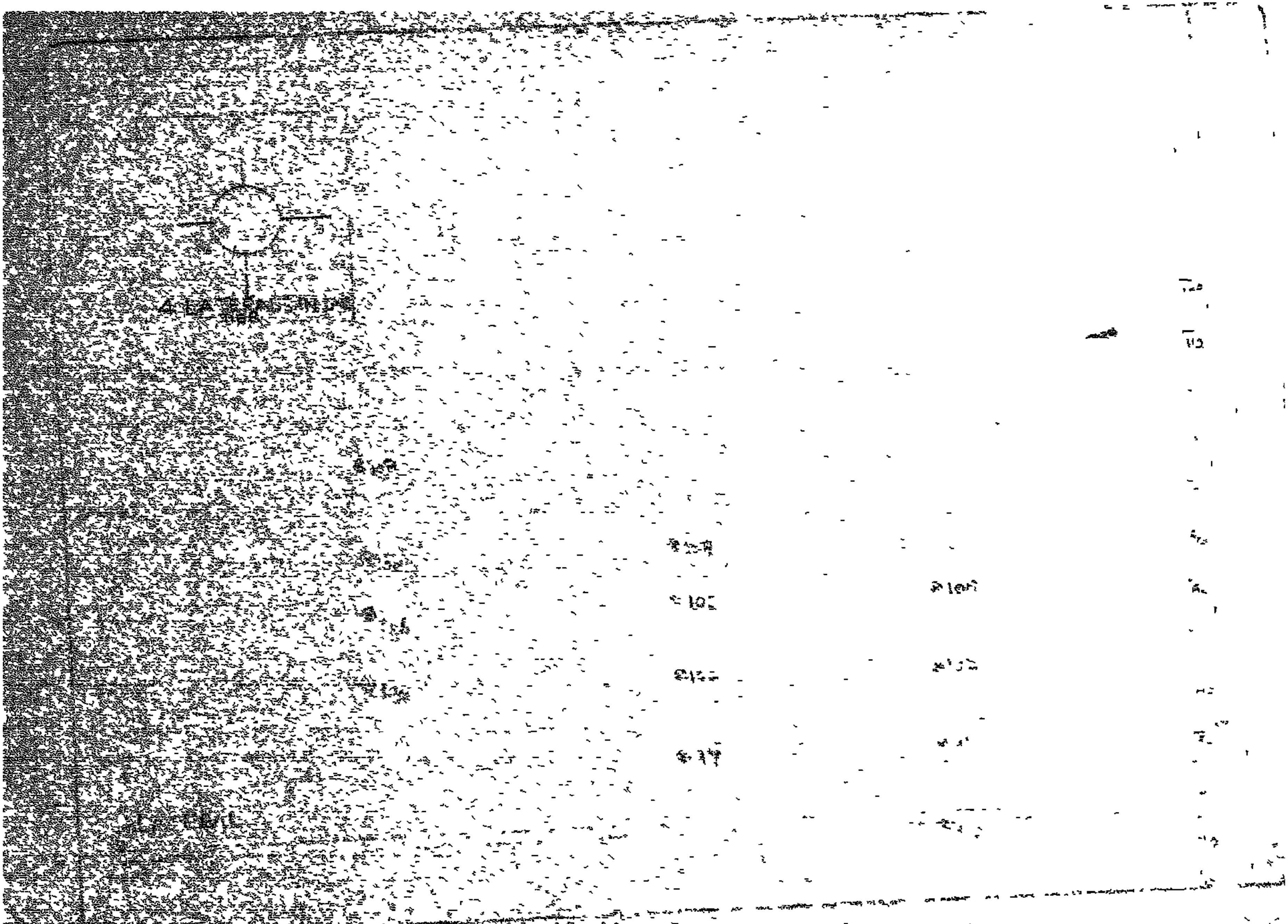


FIG. 10F [illegible] HEAD [illegible] 1550 [illegible]

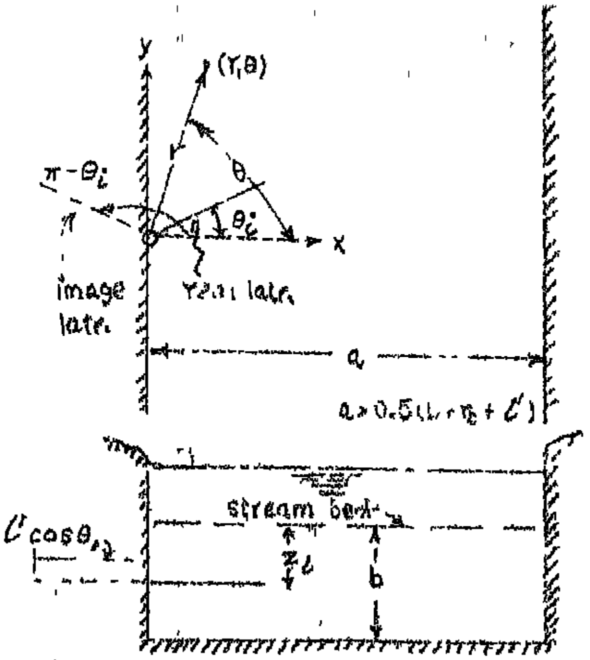


FIG # 11.

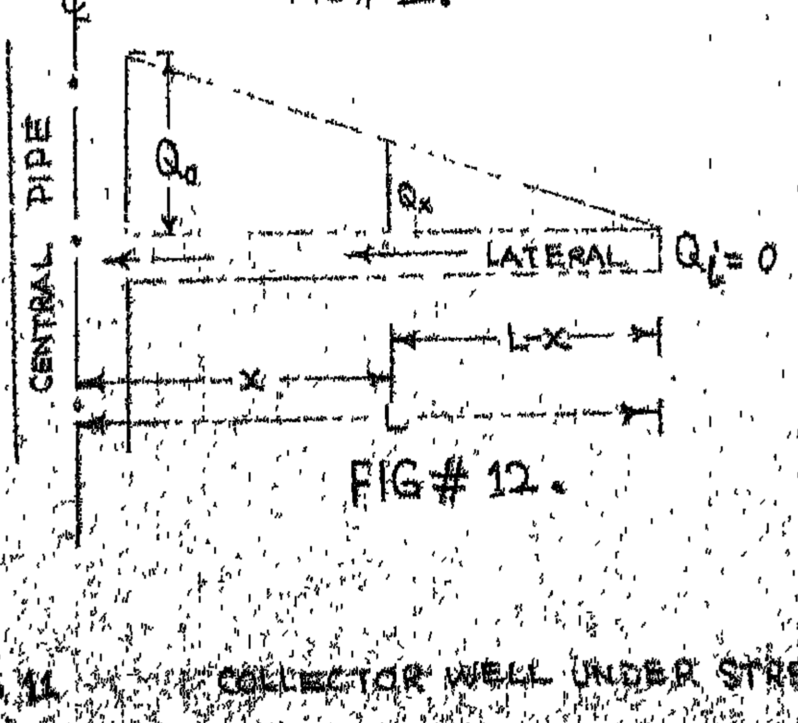
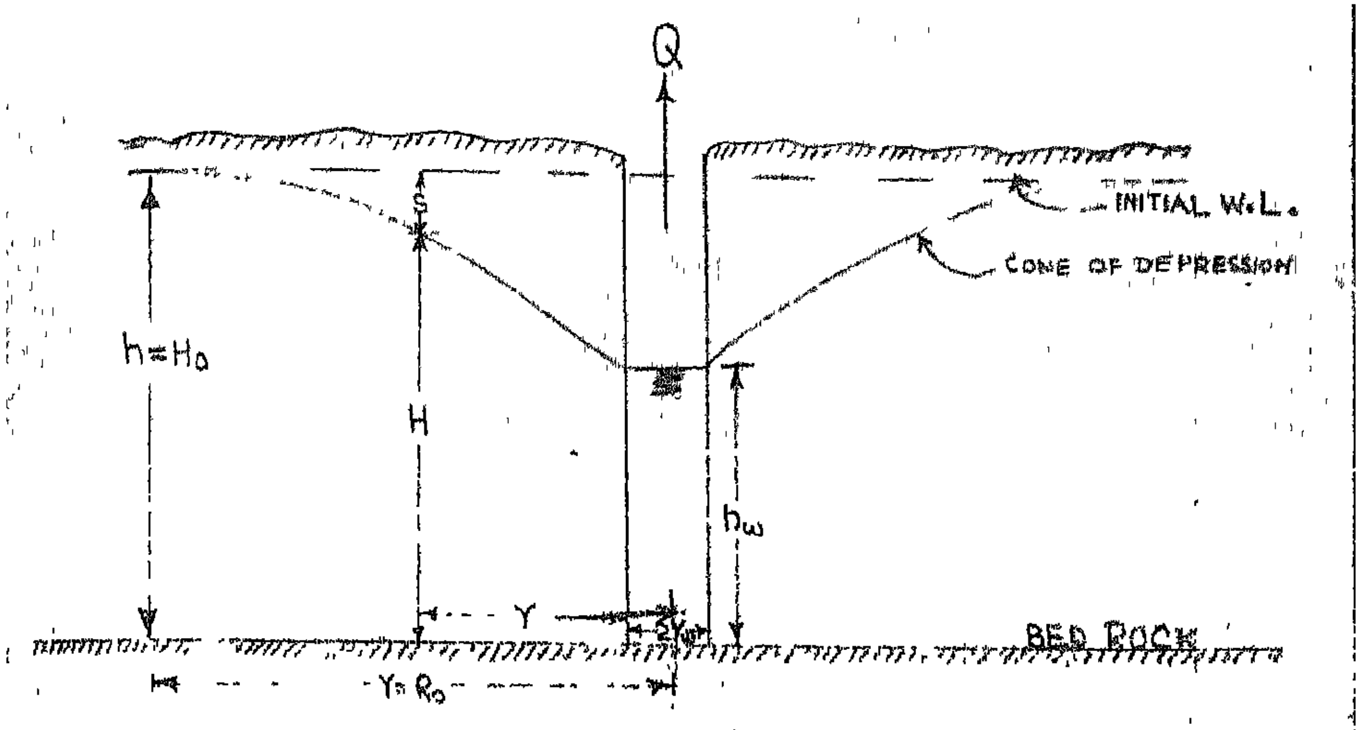


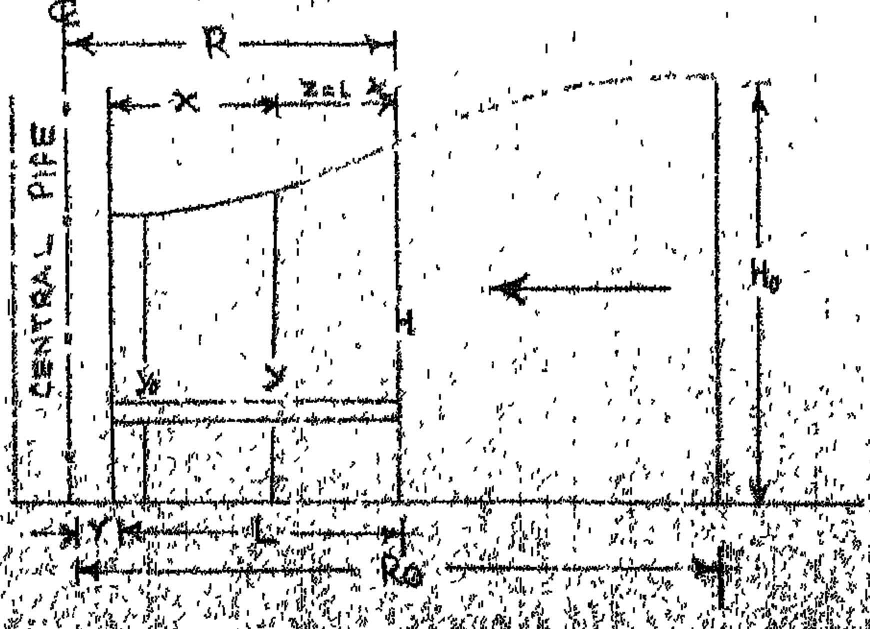
FIG # 12.

FIG 11 COLLECTOR WELL UNDER STREAM BED [REF. [illegible]]

FIG 12. A LATERAL WITH ASSUMED LINEAR DISTRIBUTION OF DISCHARGE.



FIG#13: DRAWDOWN CURVE UNDER STEADY STATE CONDITION.



FIG#14 : DRAWDOWN IN THE CASE OF A SINGLE LATERAL (REF 48)

THE NUMBERS REFER TO THE LENGTH IN INCHES (ABOVE THE STEEL PLATE) AT WHICH THE PIEZOMETRIC TIPS ARE LOCATED.

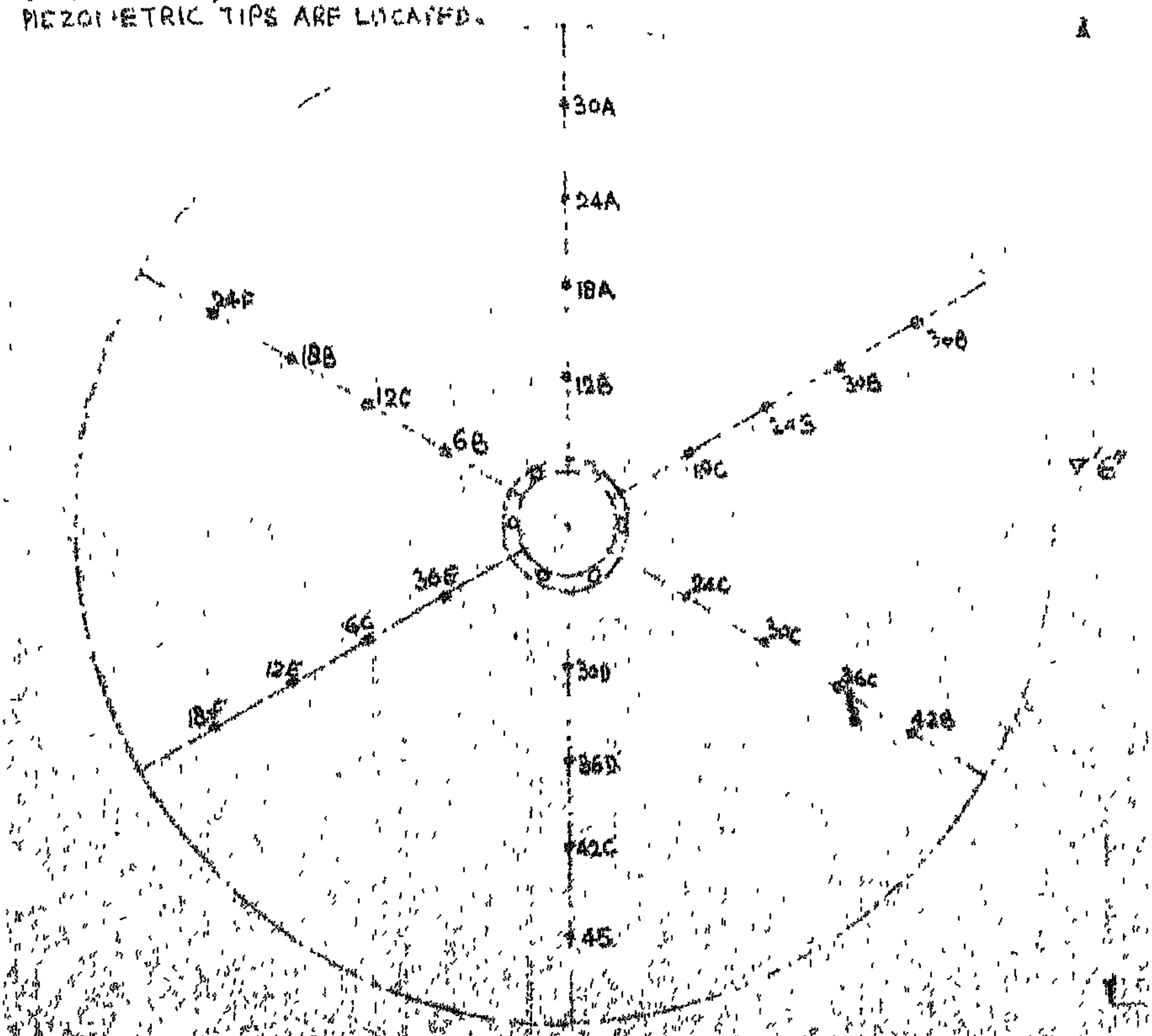


FIG # 15. LOCATION OF PIEZOMETERS IN PLAN.

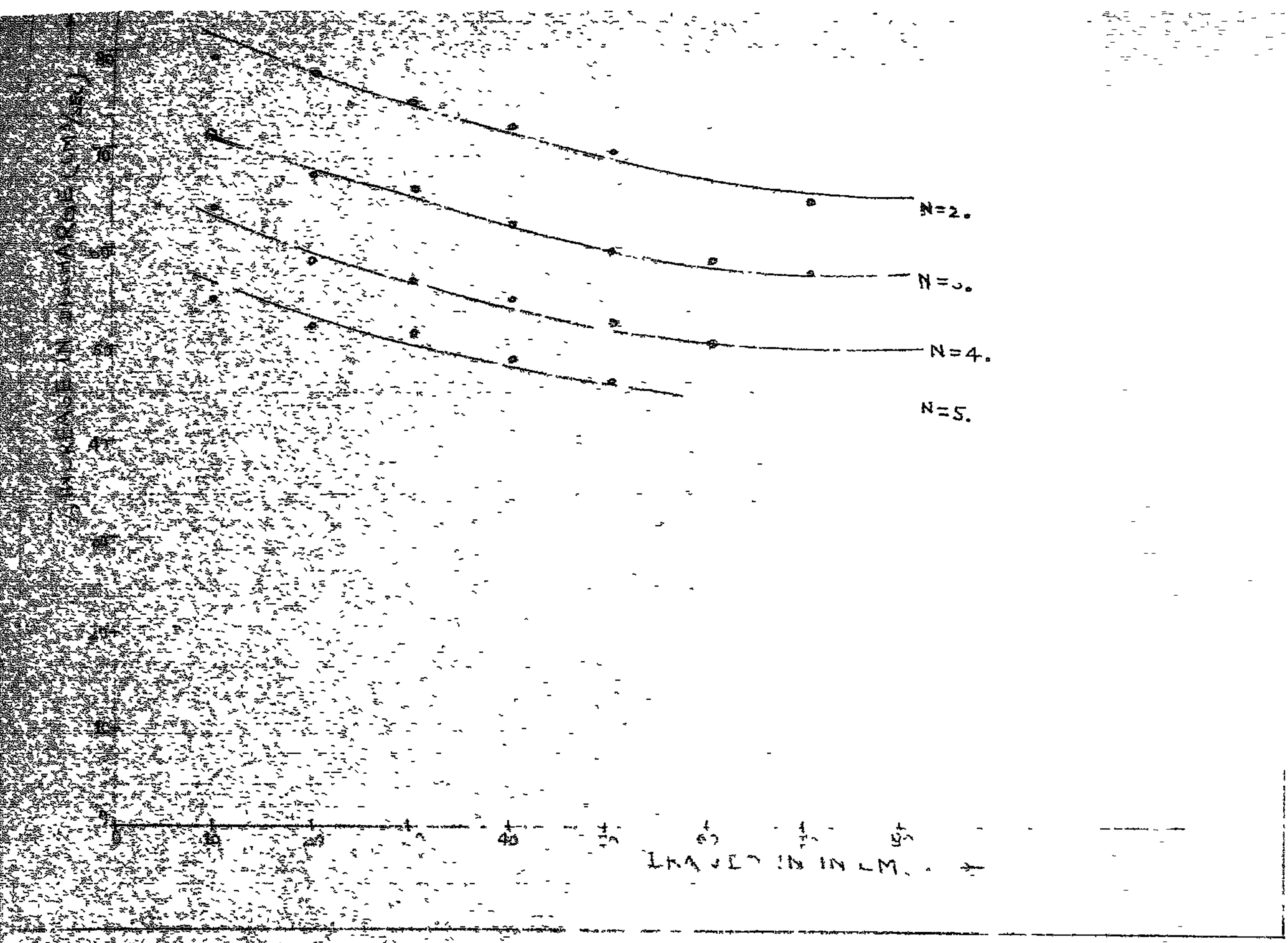
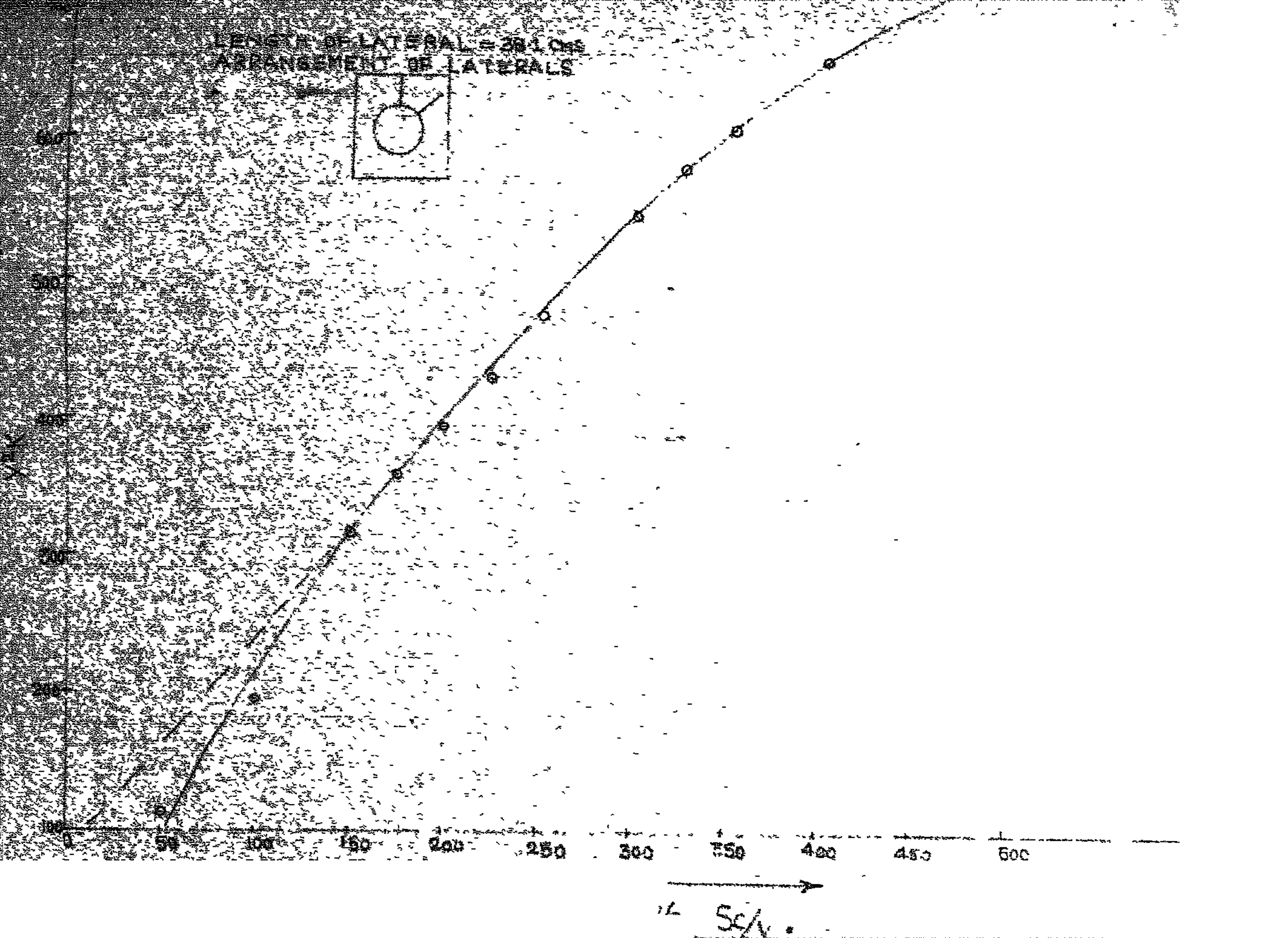


FIG. # PLOT SHOWING PERCENTAGE OF INTERFERENCE ON DISCHARGE WITH VARIOUS



LENGTH OF LATERAL = 38.1 Cms
ARRANGEMENT OF LATERALS
0
50
100
150
200
250
300
350
400
450
500

APPENDIX 1

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APPENDIX 3

$$Q_4 - Q_2 = c$$

where c is a constant

$$Q_8 - Q_4 = c$$

$$Q_{16} - Q_8 = c$$

$$Q_{2^i} - Q^{(i-1)} = c$$

Summing we get

$$Q_{2^i} = (i-1)\ c + Q_2$$

where $2^i = n$

or $$i = \frac{\log n}{\log 2}$$

$$Q_2 = 1.0$$

or $$Q(n) = Q_2 \left[\left(\frac{\log n}{\log 2} - 1 \right) c + 1 \right]$$

$$c = .55 \text{ from graph}$$

$$Q(n) = \left[1 + .8 \log_e (n/2) \right] \quad \text{For } n = 2,4,8,16$$

Similarly for unsymm case

$$Q(n) = Q_2 \left[(n-2)\ c + 1 \right]$$

$$c = .4 \text{ from graph}$$

or $$Q(n) = Q_1 \left[(n-2)\ .4 + 1 \right]$$

APPENDIX – 4

[illegible]	[illegible] Various discharges in [illegible]/sec				[illegible] 16" [illegible] Various discharges in [illegible]/sec			
	[illegible]	946	1090	1120	430	600	1010	1560
6B	90.0	85.0	85=					
12B	107.0	105.5	105.8	105.0	105.2	105.0	101.5	99.5
12B	107.0	105.5	105.8	105.0	105.2	105.0	101.5	99.5
18C	107.4	105.6	106.8	106.0	106.8	106.8	105.0	104.5
24C	107.5	107.5	107.0	106.5	105.5	108.0	105.5	105.0
30D	108.0	108.0	108.0	107.2	106.0	108.0	106.5	106.0
36E	108.5	108.0	108.3	107.8	106.8	108.0	107.0	106.5
12C	105.4	105.1	104.0	103.5	105.0	101.5	101.0	99.0
18A	107.8	106.5	107.0	106.4	106.5	106.8	105.0	103.8
24B	107.8	106.5	107.2	106.8	107.0	107.0	105.8	106.0
30C	108.0	108.0	108.0	107.2	105.6	108.8	106.8	106.0
36D	108.0	108.4	108.5	108.0	106.1	108.2	106.6	107.0
6C	102.0	98.3	98.4	98.5	104.5	104.5	100.0	97.5
18B	107.0	106.0	105.0	104.0	106.0	105.0	104.0	103.0
24A	108.0	107.8	108.0	107.6	107.0	108.0	107.0	106.2
30B	108.0	107.4	108.2	108.0	106.6	107.8	108.0	108.0
36C	108.2	109.0	109.0	108.0	106.0	109.0	107.2	107.0
42C	108.8	109.0	109.0	108.5	106.4	109.0	103.0	108.0
12E	106.6	104.8	105.0	104.0	106.0	106.5	104.0	102.5
24F	108.0	108.0	108.0	108.0	108.0	108.0	103.0	108.0
30A	108.5	108.5	109.0	108.8	107.6	108.5	108.0	108.0
36B	108.0	108.4	108.6	108.8	106.6	107.8	108.0	108.0
42B	108.8	109.5	109.4	108.8	106.4	109.4	108.0	108.0
45	109.5	109.0	109.0	109.0	110.0	110.0	110.0	110.0
OM	81.0	38.0	34.0	28.0	94.0	89.0	70.0	53.0

Name of piezomet	with that wall the st[illegible] ([illegible]) [illegible] Various discharges in [illegible]/sec				with all the [illegible] (small) [illegible] Various discharges in [illegible]/sec			
	4000	987	[illegible]	1425	1490	2200	3108	[illegible]
6B	106.5	105.0	103.0	101.5	94.4	85.5	77.0	0.0
12B	104.5	100.8	97.8	87.5	74.0	60.0	100.0	0.0
18C	100.0	91.0	86.0	78.0	91.0	79.0	69.5	0.0
24C	104.6	102.0	99.0	96.5	98.3	91.0	88.0	0.0
30D	107.0	106.7	106.5	104.0	106.0	105.0	93.5	0.0
36E	107.0	106.7	105.5	104.8	104.0	103.0	100.5	0.0
12C	107.0	106.0	105.0	104.0	105.0	104.0	103.0	0.0
18A	106.0	103.8	101.0	99.0	95.0	86.5	80.0	0.0
24B	104.5	101.4	98.0	96.0	100.0	93.0	89.5	0.0
30C	106.0	105.0	103.0	101.5	104.0	103.6	96.0	0.0
36D	107.5	107.6	106.0	105.5	108.0	107.0	102.0	0.0
6C	107.0	107.0	105.0	104.2	102.4	98.0	95.0	0.0
18B	108.0	108.0	108.5	106.0	103.5	99.0	98.0	0.0
24A	107.2	107.0	105.0	104.6	103.0	98.0	97.0	0.0
30B	108.0	107.0	106.1	105.0	107.0	106.6	100.0	0.0
36C	107.5	107.9	106.5	106.0	106.5	108.0	103.5	0.0
42C	107.5	108.0	107.5	106.5	108.0	109.0	107.0	0.0
12E	107.8	108.0	106.4	106.0	105.0	101.5	100.8	0.0
24F	109.0	109.0	108.0	107.8	107.0	103.0	104.0	0.0
30A	108.4	109.0	108.0	107.0	107.0	109.0	106.0	0.0
36B	107.5	108.0	107.0	106.5	107.0	109.0	106.8	0.0
42B	108.0	108.8	107.5	107.2	108.0	109.0	107.0	0.0
45	109.0	109.0	109.0	109.2	109.2	109.0	109.0	0.0

[illegible]	[illegible]				[illegible]			
	[illegible]				[illegible]			
	504	538	1480	[illegible]	466	910	[illegible]	[illegible]
6B	102·0	96·5	89·0	80·0	102·8	98·6	94·0	86·0
12B	98·0	89·0	80·5	60·5	99·2	93·0	90·0	73·0
18C	104·0	100·0	95·0	88·0	108·0	106·9	106·0	104·0
24C	106·0	105·0	102·5	98·5	106·2	104·0	102·5	99·0
30D	107·3	108·0	106·6	104·2	106·0	106·0	106·0	104·0
36E	107·5	108·2	107·0	105·0	108·0	107·0	106·6	105·0
12C	107·0	106·0	105·0	104·0	107·0	106·0	105·0	104·0
18A	104·0	101·2	97·0	90·5	105·0	102·0	99·6	94·8
24B	106·0	105·0	102·5	98·5	107·0	105·0	104·0	100·5
30C	107·0	107·0	106·0	103·5	107·3	105·5	105·0	103·0
36D	108·0	108·5	108·0	106·0	108·2	107·0	107·0	[illegible]
6C	106·5	106·0	103·5	100·0	106·8	104·4	103·0	100·0
18B	107·0	106·6	105·0	102·0	108·0	106·5	103·8	103·5
24A	107·0	106·6	105·0	102·0	104·5	101·0	97·6	91·5
30B	107·5	108·0	107·5	105·0	108·0	107·5	107·5	106·5
36C	108·0	108·5	108·2	107·0	109·0	107·5	108·0	107·0
42C	108·0	109·0	109·0	108·0	108·6	107·6	108·0	107·0
12E	107·5	108·0	106·5	104·0	108·0	106·4	105·0	104·0
24F	109·0	108·5	108·0	106·0	109·0	108·0	108·0	107·5
30A	108·0	109·0	108·2	106·5	109·0	108·3	108·4	108·0
36B	108·0	108·4	108·0	107·0	108·5	108·0	108·0	107·5
42B	108·0	109·0	108·0	108·0	109·0	108·0	108·4	108·0
45	110·0	110·0	109·0	109·0	110·0	109·0	109·0	108·5
0M	94·5	82·0	64·0	39·0	97·5	89·0	79·0	60·0

Name of piezometer	With slot in IInd [illegible]				[illegible] 8 slot in all the slots [illegible]			
	Various discharges in [illegible] ml/sec				Various discharges in [illegible] ml/sec			
	223	504	600	[illegible]	538	1518	2565	3680
6B	108·0	106·2	105·5	106·0	106·0	101·0	92·0	88·0
12B	97·5	91·0	86·5	80·0	107·0	105·0	102·0	88·0
18C	106·3	103·4	101·5	102·0	106·6	101·6	95·4	92·0
24C	108·0	106·8	106·0	106·6	106·6	105·0	98·0	95·0
30D	109·5	108·1	108·0	109·0	107·0	106·5	102·4	102·0
36E	107·6	107·0	106·8	108·0	107·5	106·8	104·0	103·0
12C	108·0	107·0	106·0	103·0	107·0	106·0	105·0	104·0
18A	107·0	104·8	103·5	103·2	106·5	103·0	97·0	94·5
24B	108·5	106·6	106·0	106·0	107·0	104·2	101·5	99·0
30C	109·0	107·8	107·5	108·0	108·0	107·5	104·0	103·0
36D	109·8	108·5	108·0	109·5	108·0	107·8	105·0	104·0
6C	109·5	108·0	107·5	108·3	106·1	102·0	94·0	92·0
18B	109·8	108·2	108·0	108·8	107·0	106·0	105·0	104·0
24A	109·5	108·0	107·5	108·0	107·4	106·0	103·0	103·0
30B	108·0	107·5	107·5	108·0	107·0	106·0	105·5	104·5
36C	110·0	109·0	109·0	110·0	107·5	108·0	105·0	106·5
42C	110·0	109·0	109·0	110·0	108·0	109·0	107·0	108·0
12E	110·0	108·6	108·2	109·0	106·8	103·5	97·5	96·0
24F	110·0	109·0	109·0	109·5	110·0	110·0	109·0	110·0
30A	110·2	109·0	109·0	109·8	108·0	108·0	107·0	107·0
36B	109·0	108·0	108·0	109·0	107·0	106·0	106·5	106·0
42B	110·0	109·0	109·0	110·0	108·0	109·0	107·0	107·0
45	110·0	108·0	108·5	110·0	110·0	110·0	109·0	109·0
0M	81·5	67·5	55·5	41·0	98·0	93·0	88·0	82·0

[illegible]				[illegible]			
[illegible]				[illegible]			
315	[illegible]	[illegible]	[illegible]	405	[illegible]	[illegible]	[illegible]
105.5	103.8	97.0	95.5	106.5	105.0	104.0	104.0
106.0	105.0	105.0	104.0	94.0	85.0	80.5	74.0
104.5	102.0	94.0	92.5	103.0	100.0	93.0	97.0
107.0	106.0	103.0	101.0	106.5	105.5	104.5	105.0
108.0	108.0	106.0	106.0	108.0	107.0	107.0	108.0
108.0	108.0	106.0	106.0	107.2	107.0	106.2	107.2
106.0	106.0	105.0	104.0	105.0	104.0	103.0	102.0
105.0	103.5	96.0	94.5	105.0	102.5	101.0	100.6
107.0	106.2	102.0	101.0	106.5	105.0	104.0	104.0
108.0	108.0	107.0	105.0	107.3	107.0	106.0	107.0
108.8	108.8	107.5	107.0	108.5	108.0	107.5	108.5
107.8	107.5	97.0	95.5	108.0	107.0	106.5	107.0
108.0	107.8	104.5	103.5	107.5	106.0	107.0	108.0
108.0	107.6	104.5	103.0	108.0	107.0	106.4	107.0
107.5	107.5	106.0	105.0	108.0	107.5	107.5	108.0
109.0	109.0	108.0	107.5	108.8	108.0	108.0	109.0
108.0	107.5	107.0	106.0	109.0	106.5	108.0	109.5
108.5	108.5	106.0	105.0	108.5	108.0	107.5	109.0
109.0	109.0	108.2	108.0	109.0	109.0	109.0	109.5
109.0	109.0	108.0	108.0	109.0	108.5	108.0	109.0
108.5	108.5	108.0	108.0	108.5	108.0	108.0	108.5
109.0	108.8	108.5	108.0	109.0	108.5	108.0	109.5
109.0	109.0	108.5	108.0	110.0	110.0	110.0	110.0
93.0	81.5	38.0	20.0	85.0	67.5	55.0	40.0

With 4 lat in IIIrd tier (small) [illegible]				With 4 lat in IIIrd tier (S [illegible]) [illegible]			
Various discharges in [illegible]				Various discharges [illegible]			
465	678	965	1280	562	952	1200	0.0
105.0	105.0	103.0	103.0	105.0	103.8	103.0	0.0
102.2	101.0	98.0	97.0	103.0	99.5	98.0	0.0
97.0	93.6	88.0	85.0	98.3	91.0	87.0	0.0
104.0	103.5	101.0	100.6	102.5	98.5	97.0	0.0
107.0	107.0	106.0	106.5	106.3	104.5	105.0	0.0
106.6	107.0	106.0	106.5	107.0	106.5	105.0	0.0
104.0	103.0	102.0	101.0	104.0	103.0	102.0	0.0
100.2	98.5	94.5	93.0	101.3	96.5	94.5	0.0
103.0	102.0	99.5	98.8	103.5	100.0	99.0	0.0
106.5	106.0	104.5	105.0	105.0	104.0	103.0	0.0
107.0	108.0	107.0	108.0	106.5	106.0	106.5	0.0
106.8	107.4	106.0	106.5	106.5	105.9	106.0	0.0
106.5	107.0	105.4	105.6	106.8	105.0	105.8	0.0
106.0	106.0	104.3	104.2	106.4	104.5	104.5	0.0
106.5	107.0	106.5	106.0	106.0	105.0	105.0	0.0
107.5	108.4	107.5	108.0	107.8	107.0	107.2	0.0
108.0	108.4	108.2	109.0	108.0	108.0	108.5	0.0
107.1	108.1	107.0	108.0	107.2	106.8	107.1	0.0
109.0	109.0	108.5	108.0	108.0	108.0	108.5	0.0
108.0	108.5	107.5	108.0	108.0	107.0	108.0	0.0
107.0	108.0	107.5	108.0	108.0	107.0	108.0	0.0
108.0	108.4	108.4	109.0	108.0	108.0	108.5	0.0
110.0	109.2	109.2	110.0	109.5	109.2	109.0	0.0
86.5	75.5	59.0	32.0	89.5	72.0	57.5	0.0

No. of [illegible]	[illegible]				[illegible]			
	[illegible]				[illegible]			
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6B	105•0	104•0	102•0	101•0	100•0	95•0	91•5	84•0
12B	103•5	102•8	99•0	97•5	101•6	98•0	95•5	89•0
18C	106•0	105•0	103•3	102•8	106•5	104•0	103•5	102•5
24C	107•0	107•0	106•0	105•5	106•0	104•8	104•6	102•5
30D	108•0	108•0	108•0	107•5	107•0	107•0	107•0	106•0
36E	107•0	106•0	104•0	103•0	107•0	107•0	106•0	105•0
12C	106•0	105•7	104•2	103•5	103•5	103•0	102•5	[illegible]•2
18A	107•5	107•0	106•6	105•5	106•0	106•0	106•0	103•5
24B	107•5	108•0	107•0	106•8	106•5	106•0	105•5	105•0
30C	109•0	108•8	108•5	108•0	107•0	107•0	108•0	107•0
36D	107•2	107•0	106•2	105•5	105•0	104•0	103•5	100•6
6C	108•0	108•0	107•8	107•0	107•0	106•5	106•2	105•0
18B	108•0	108•0	107•5	107•0	107•0	102•[illegible]	101•0	97•5
24A	108•0	108•0	108•0	107•5	107•5	107•0	107•8	107•4
30B	108•0	108•0	108•0	108•0	107•5	108•0	108•0	106•0
36C	108•0	108•0	108•0	107•0	107•8	108•0	108•0	107•3
42C	108•0	108•0	107•6	107•0	106•8	106•5	106•5	105•0
12E	108•8	109•0	109•0	108•0	108•0	108•0	109•0	108•0
24F	108•8	109•0	109•0	108•4	108•5	108•5	108•0	106•0
30A	109•0	108•8	108•5	108•0	108•0	108•0	108•0	108•0
36B	109•0	108•6	108•0	108•4	108•6	108•2	109•0	108•6
42B	109•0	109•0	109•0	109•0	109•0	109•0	108•0	108•0
45	109•0	108•0	106•5	108•0	108•0	108•0	107•0	106•5
OM	80•0	64•0	45•0	33•0	89•0	74•0	53•0	29•0

No. of horizontal	with 2 slat in III rd bay (Small [illegible])				with 2 slat in III rd bay (Small [illegible])			
	Vibration [illegible] in [illegible]/sec				Vibration [illegible]/sec			
	370	416	575	630	[illegible]	615	708	[illegible]
6B	108•4	107•2	107•8	108•2	107•8	106•8	106•0	104•4
12B	106•5	104•6	104•5	105•0	103•0	101•4	98•5	107•0
18C	106•5	104•6	104•2	104•5	105•0	103•3	102•0	100•0
24C	109•0	107•6	108•0	108•9	108•0	107•0	103•0	107•0
30D	108•8	107•7	108•0	109•0	106•2	107•6	107•5	106•5
36E	106•0	105•0	104•0	103•0	105•0	104•0	103•0	101•0
12C	104•2	101•5	100•8	100•0	101•0	100•0	97•7	94•5
18A	106•8	105•5	105•0	105•0	104•0	103•0	102•0	98•0
24B	108•0	106•8	107•0	107•5	107•0	106•0	106•5	104•0
30C	109•0	108•2	108•4	109•5	108•7	108•0	108•0	107•0
36D	109•0	108•0	108•8	109•6	108•6	108•0	108•0	107•4
6C	109•5	108•5	109•0	110•0	109•0	108•0	108•0	107•0
18B	108•8	107•5	107•1	108•2	108•0	107•0	106•2	104•2
24A	108•0	107•5	107•5	108•0	107•5	107•0	106•5	105•0
30B	109•6	108•0	109•0	109•8	108•8	108•0	108•0	107•2
36C	109•4	108•5	109•0	109•5	109•0	108•6	109•0	108•0
42C	109•6	108•8	109•0	110•0	109•0	108•5	108•5	107•0
12E	110•0	109•0	109•7	110•6	110•0	109•0	109•0	108•0
24F	110•0	109•0	109•5	110•5	109•1	108•6	108•8	107•5
30A	109•0	108•0	109•0	109•4	108•8	108•0	108•0	107•5
36B	109•6	109•0	109•2	109•5	109•0	108•6	109•0	108•0
42B	110•0	109•2	109•5	110•0	109•5	109•0	109•0	109•3
45	83•0	71•0	62•0	49•5	86•5	76•0	62•0	40•0
OM	105•8	104•0	100•0	98•5	104•2	102•0	99•5	98•0

No. of piezometer	[illegible]				[illegible]			
	Various discharges in cc/sec				Various discharges in cc/sec			
	370	416	505	600	358	516	[illegible]	[illegible]
6B	108.4	107.2	107.[illegible]	103.[illegible]	107.[illegible]	[illegible]	105.[illegible]	104.6
12C	106.5	104.[illegible]	104.[illegible]	104.5	105.0	102.6	101.4	[illegible]
18C	107.0	104.[illegible]	102.5	101.[illegible]	[illegible]	[illegible]	101.5	101.0
24C	106.6	104.6	104.2	104.5	105.0	103.3	102.[illegible]	100.0
30D	109.0	107.6	107.[illegible]	109.[illegible]	[illegible]	107.0	109.0	107.0
36E	108.0	107.7	107.[illegible]	[illegible]	108.2	107.[illegible]	107.5	106.5
12C	106.0	105.0	104.0	103.0	105.0	104.0	103.5	101.0
18A	104.2	101.5	105.8	100.0	101.0	100.0	97.7	[illegible]
24B	106.8	105.5	105.[illegible]	105.0	104.0	[illegible]	102.0	[illegible]
30C	109.0	106.[illegible]	107.0	107.[illegible]	107.0	[illegible]	105.	104.0
36D	109.0	108.2	108.4	107.5	107.7	107.[illegible]	103.0	107.0
6C	109.0	109.0	108.[illegible]	109.0	[illegible]	109.0	103.0	107.4
18B	109.5	108.5	109.0	110.0	109.0	109.0	103.0	107.3
24A	103.8	107.5	107.1	105.2	108.0	107.0	105.2	104.2
30B	103.0	107.5	107.5	108.0	107.5	107.0	106.5	105.0
36C	109.6	108.0	109.0	103.8	108.0	108.0	108.0	107.2
42C	109.4	108.5	109.0	109.5	109.0	108.0	109.0	109.0
12E	109.6	108.8	109.0	110.0	109.0	109.5	109.5	107.0
24F	110.0	109.0	109.7	110.6	110.0	109.0	109.0	108.0
30A	110.0	109.0	109.5	110.5	109.1	108.6	103.8	107.5
36B	109.0	108.0	109.0	109.4	108.9	109.0	103.0	107.5
42B	109.6	109.0	109.2	109.5	109.0	109.6	103.0	108.0
45	110.0	109.2	109.5	110.0	107.5	109.0	109.0	109.3
OM	83.0	71.0	62.0	[illegible]	36.5	[illegible]5.0	62.0	40.0

No. of piezometer	With 2 slat in I[st] & 2 in II[nd] tubes (5m [illegible])				With 1 slat in 1st & [illegible] in II[nd] tubes ([illegible])			
	Various discharges in cc/sec				Various discharges in cc/sec			
	535	755	988	12(?)	540	9 8	12[illegible]	1490
6B	105.8	104.0	100.0	98.5	104.2	102.0	99.5	98.0
12B	96.8	90.5	77.5	70.5	94.0	87.5	78.0	70.0
18C	105.0	102.8	98.0	96.5	102.0	99.1	95.0	92.0
24C	106.0	105.0	103.0	102.0	105.5	104.2	101.2	101.0
30D	108.0	108.0	106.5	106.5	107.5	106.8	105.0	106.0
36E	108.0	108.0	107.5	107.0	108.0	107.2	106.4	107.0
12C	107.0	106.0	105.0	104.0	107.0	106.0	105.0	104.0
18A	105.0	103.2	99.5	98.0	104.0	101.0	93.0	96.0
24B	107.0	106.0	104.0	105.4	105.0	103.2	102.0	101.0
30C	108.0	107.0	106.0	105.5	107.0	106.5	104.8	105.0
36D	108.5	108.0	107.5	107.0	108.5	107.5	105.6	107.0
6C	108.0	107.0	105.5	105.0	106.8	106.0	105.6	104.8
18B	108.5	108.0	107.0	106.5	108.0	107.0	105.2	106.4
24A	108.0	107.5	106.1	105.4	106.0	106.0	105.0	105.0
30B	108.5	108.0	107.5	107.5	108.5	108.0	107.5	107.5
36C	109.0	108.8	108.0	108.0	108.2	108.0	107.0	107.5
42C	109.0	109.0	108.2	108.0	109.0	108.0	107.5	108.0
12E	108.5	108.0	107.5	107.0	108.0	107.0	106.6	107.0
24F	109.0	108.8	108.5	108.2	109.0	108.4	108.0	108.0
30A	109.0	109.0	108.0	108.2	108.2	108.0	108.0	108.0
36B	108.0	108.0	108.0	108.0	108.0	108.0	108.0	108.0
42B	109.0	109.0	109.0	109.0	109.0	108.5	108.0	108.0
45	110.0	110.0	109.0	109.0	110.0	109.0	109.0	108.0
[illegible]	[illegible]	[illegible]	40.0	33.0	28.0	78.0	62.0	44.0

Name of piezometer	With 4 lat 3" ... (long)				With 8 lat 6" ... (long)			
	Various discharges in cusecs				Various discharges in cusecs			
	262	450	650	850	510	1060	1260	2125
6B	103.0	99.0	95.[illegible]	91.0	[illegible].0	92.0	[illegible]	74.0
12B	104.5	102.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	96.9
18C	106.0	104.9	103.	101.0	[illegible]	104.6	101.0	96.0
24C	107.0	106.0	[illegible]	102.5	[illegible]	104.	103.0	100.0
30D	107.4	107.0	106.[illegible]	105.0	107.0	106.0	105.0	103.0
36E	107.6	107.5	107.0	106.0	107.0	106.[illegible]	105.4	104.0
12C	107.0	106.0	105.0	104.	107.0	106.[illegible]	105.0	104.0
18A	106.4	105.0	104.[illegible]	102.[illegible]	[illegible].4	103.4	101.[illegible]	97.0
24B	107.5	106.9	106.	105.0	10[illegible]	105.[illegible]	104.0	102.0
30C	107.6	107.[illegible]	[illegible]	[illegible]	[illegible]	104.4	103.5	101.[illegible]
36D	107.8	[illegible]	107.2	106.[illegible]	107.1	106.5	105.0	105.0
6C	104.[illegible]	101.[illegible]	95.[illegible]	[illegible]5.0	[illegible]	96.0	[illegible]2.0	93.0
18B	107.[illegible]	106.9	106.[illegible]	105.0	106.8	105.5	10[illegible].6	102.0
24A	108.0	108.0	107.0	106.5	107.8	107.0	105.5	104.2
30B	108.0	108.0	108.0	107.5	107.5	107.5	107.0	106.9
36C	108.0	108.4	108.2	107.9	1[illegible]7.4	107.0	106.8	107.5
42C	106.0	106.0	105.7	105.0	105.3	105.5	105.1	103.0
12E	106.0	106.0	105.2	105.0	10[illegible].5	105.5	105.1	105.0
24F	108.4	108.2	108.0	108.[illegible]	[illegible].5	108.0	108.0	107.0
30A	108.6	109.[illegible]	109.[illegible]	108.5	10[illegible].0	108.9	108.2	108.0
36B	108.0	109.0	108.4	108.0	10[illegible].0	109.0	108.0	108.0
42B	110.4	109.4	109.3	108.2	107.9	109.6	108.6	108.4
45	110.0	110.0	110.0	109.0	110.0	109.0	110.7	1[illegible].0
OM	91.0	81.0	64.6	43.[illegible]	[illegible]4.0	82.0	71.0	40.0

Name of piezometer	with 8 lat 6" above bed (long) syn				with 2 lat in ... (long)			
	Various discharges in cub/sec				Various discharges in cub/sec			
	390	900	1160	2860	605	755	989	1279
6B	106.0	102.0	77.0	73.0	[illegible]1.9	91.0	85.0	83.0
12B	108.0	105.8	95.1	96.0	101.0	98.5	90.0	96.0
18C	108.1	107.1	101.4	102.0	107.0	107.[illegible]	104.0	103.4
24C	109.0	107.0	106.0	98.8	106.0	106.5	104.0	103.5
30D	109.4	107.0	104.0	102.0	106.5	107.0	105.0	105.0
36E	109.5	107.0	105.8	104.0	103.9	102.8	102.0	102.0
12C	109.2	107.0	103.0	102.0	106.0	107.0	105.0	103.0
18A	109.2	106.8	101.1	101.4	105.8	106.0	102.3	102.0
24B	109.4	107.4	104.3	104.0	106.4	107.5	105.0	105.0
30C	109.5	106.4	105.2	102.0	107.0	107.2	105.0	105.0
36D	108.4	107.0	104.0	103.0	107.0	108.0	105.0	105.0
6C	104.0	100.5	90.0	86.0	104.0	103.8	99.0	97.8
18B	108.0	107.0	106.0	105.0	106.0	102.0	101.0	101.0
24A	108.6	107.8	104.3	106.5	107.0	107.4	105.4	105.0
30B	107.0	106.0	107.0	105.0	107.0	108.0	107.0	108.0
36C	109.8	107.0	106.0	103.2	107.2	108.2	105.0	106.0
42C	108.8	107.5	105.8	104.2	106.5	106.0	105.0	105.0
12E	107.8	105.8	99.0	96.5	105.8	106.0	102.8	102.0
24F	109.0	108.5	108.0	107.0	108.0	108.0	107.5	107.1
30A	109.0	108.0	107.5	106.8	107.5	109.0	107.5	107.0
36B	107.8	108.0	108.2	107.0	105.0	108.0	107.0	107.0
42B	108.4	108.0	107.5	107.0	107.0	108.4	107.0	107.0
45	110.0	109.0	110.0	109.0	110.0	110.0	109.8	110.0
OM	104.8	83.8	30.0	27.0	90.1	83.0	64.0	50.0

[illegible]	[illegible]				[illegible]			[illegible]
	[illegible]				[illegible]			[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6B	102.0	101.5	100.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12B	106.8	105.8	102.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18C	108.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24C	107.0	[illegible]	106.8	104.4	[illegible]	106.0	104.4	[illegible]
30D	107.6	[illegible]	107.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
36E	108.1	[illegible]	[illegible]	106.0	[illegible]	[illegible]	[illegible]	106.0
12C	[illegible]	107.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18A	108.0	[illegible]	106.1	[illegible]	[illegible]	104.1	103.2	[illegible]
24B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	105.0	[illegible]	[illegible]
30C	107.0	[illegible]	[illegible]	[illegible]	[illegible]	107.4	106.0	[illegible]
36D	107.6	[illegible]	107.5	[illegible]	[illegible]	107.8	107.0	[illegible]
6C	106.8	107.0	[illegible]	[illegible]	[illegible]	100.5	[illegible]	[illegible]
18B	107.0	[illegible]	[illegible]	104.0	[illegible]	106.0	[illegible]	104.0
24A	108.0	107.8	[illegible]	105.5	[illegible]	106.4	105.4	105.0
30B	109.0	109.0	[illegible]	106.5	[illegible]	107.0	[illegible]	[illegible]
36C	107.2	[illegible]	108.0	108.0	[illegible]	[illegible]	[illegible]	[illegible]
42C	107.6	109.5	[illegible]	[illegible]	[illegible]	108.0	[illegible]	108.0
12E	107.5	108.0	105.3	[illegible]	[illegible]	103.0	101.0	[illegible]
24F	110.0	109.0	[illegible]	108.0	[illegible]	109.0	103.5	108.0
30A	109.0	110.0	103.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
36B	109.5	109.5	108.0	[illegible]	[illegible]	107.0	[illegible]	[illegible]
42B	107.4	110.4	[illegible]	[illegible]	[illegible]	107.5	[illegible]	[illegible]
45	110.0	109.5	109.8	[illegible]	[illegible]	110.0	110.0	110.0
OM	102.0	98.0	93.0	86.0	[illegible]	65.0	79.0	58.0

Name of piesomet	with lat in all the 3 tiers (Long) [illegible]				with [illegible] in all the 3 tiers (Long) [illegible]			
	Various discharges in m^3/sec				Various discharges in m^3/sec			
	439	895	1022	1855	600	1655	2225	3460
6B	106.0	102.0	96.0	88.3	104.0	102.8	97.5	98.0
12B	104.8	99.0	91.0	79.8	102.5	99.5	102.0	87.0
18C	106.0	105.0	100.8	94.6	106.0	105.0	103.0	101.0
24C	107.0	105.0	102.0	98.0	104.4	105.0	104.0	100.0
30D	107.8	106.2	104.5	100.0	105.5	106.0	106.4	103.0
36E	108.0	107.0	105.8	102.0	107.0	106.0	105.5	104.6
12C	106.0	103.0	98.3	91.8	105.5	103.0	101.0	101.0
18A	107.0	105.0	104.0	100.0	106.0	106.0	105.0	104.0
24B	108.0	107.0	105.8	101.0	105.0	106.0	105.4	103.0
30C	108.0	107.2	106.5	103.8	107.0	106.8	107.0	105.0
36D	106.8	102.8	98.0	91.0	104.5	103.0	101.0	97.0
6C	107.5	106.6	105.0	101.6	106.0	106.8	106.8	105.0
18B	108.0	107.0	106.0	105.0	108.0	107.0	105.0	105.0
24A	108.0	108.0	108.0	106.0	107.0	107.0	107.0	107.0
30B	108.5	108.0	108.0	105.0	107.5	107.0	107.0	105.0
36C	109.0	108.4	108.4	107.0	107.5	107.5	108.4	106.0
42C	107.0	104.6	101.5	96.0	105.0	105.5	101.0	100.6
12E	108.5	108.0	108.0	108.0	107.5	107.5	107.0	107.0
24F	108.5	108.5	108.4	106.8	107.6	107.5	103.0	107.8
30A	108.0	108.0	108.0	107.0	107.5	107.5	107.5	107.5
36B	109.0	109.0	109.0	108.0	107.5	107.5	103.0	107.4
42B	109.0	109.0	109.0	108.0	107.5	107.5	108.0	107.0
45	109.0	109.0	109.0	109.0	109.0	109.0	108.0	108.0
OM	100.0	97.5	81.4	60.0	100.0	91.0	73.0	58.5

634

Shukla,
Studies on horizontal collector wells.